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# Testing for the Impact Resistance of Ophthalmic Lenses

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Center for Consumer Product Technology
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

## Introduction

The Optical Manufacturers Association's Research Associate Program began at the National Bureau of Standards in February 1974. The object of this program was to develop a mechanical testing procedure for verifying the impact resistance of ophthalmic lenses 1/. The research effort was guided by the following specific objectives which were outlined at the onset of the program:

1. Collection and analysis of all available information regarding the FDA drop ball test 2/ for eyeglass lenses.
2. Identification of the limitations of the present procedure and the definition of the basic criteria for a proper test.
3. Experimental and analytical efforts to establish a procedure for a new test.

Throughout the investigation, a fundamental approach has been maintained so that specific problems concerning impact resistant lenses could be viewed in terms of the broader perspectives of fracture mechanics and statistics of fracture. Four research papers have been written.

The purpose of this report is to review, for the sponsor, the principal findings of the program, to discuss the possible alternatives to the drop ball test, and to suggest a reasonable direction for continuing the effort. First, some preliminary remarks must be made regarding impact, fracture, test methods, and damage to lenses.

Surfaces and edges of eyeglass lenses (as with all glass surfaces) contain many small microcracks or, as they are commonly called, flaws. The presence of such flaws is unavoidable and is a natural result of the finishing and edging processes. The number, severity (for now, severe flaws can be regarded as relatively deep cracks), and location of these flaws is random. For an individual lens, techniques do not exist for describing this random distribution. However, for a group of identical lenses, there are methods by which this flaw distribution can be related to the amount of breakage when lenses are subjected to increasing stress levels in a particular loading configuration.

The flaw distributions for surface flaws and edge flaws must be described separately. This is because different procedures are used in surfacing and edging and the nature of the resulting flaws reflects these differences. An estimate of the depth of surface flaws is about 1 micrometer. Edge flaws are at least an order of magnitude more severe (the edge is ground but not polished).

When a lens is impacted, tensile stresses build up in regions of both surfaces* and also on the edge. Fracture occurs when the stress in the vicinity of a flaw is sufficiently large to cause that flaw to grow catastrophically. As the number and severity of the flaws on a lens increases, the likelihood for fracture also increases. The flaw distributions on the surface and edge are then most important in describing the impact resistance of a group of eyeglass lenses.

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*In the drop ball test, the most likely surface for fracture initiation is the concave surface where stresses arise from the flexure of the lens during impact. Brandt 3/ discusses the relationship between the impact parameters and the possible sites for fracture initiation.

The net flaw distribution on a group of finished lenses also depends upon the type and quality of the strengthening technique (in the case of glass lenses). The net effect of either heat treating or chemical tempering is the existence of a surface compression region in which both surface and edge flaws are embedded. For a given flaw, more tensile stress is required to initiate fracture because the compression in the surface region must be overcome. Effectively, the severity of the flaw has been reduced. For a group of lenses, the net flaw distribution will depend upon the strengthening quality.

There are two general methods which can be used in testing for the impact resistance of the finished product; the first is a proof test. Each specimen is thoroughly inspected so that any lens containing flaws in the worst end of the distribution are rejected. Traditionally, proof tests are the safest and most expensive. A lens which passes can be guaranteed to have no flaws more severe than some specified level. Equivalently, it can be guaranteed to withstand a certain level of impact.

The other alternative is to test for the overall quality of many lenses. Essentially, one verifies that good machine shop practices are in effect. No statement is made about an individual lens. Rather, the percentage of lenses containing severe flaws is kept at some minimum level. Often this is accomplished by statistical sampling procedures.

If either of these methods involves mechanical testing (especially the proof test), the question of damage to lenses must be resolved. Damage occurs when the severity of a flaw increases by the process of slow crack growth (when the applied stress is not large enough to cause catastrophic failure). The amount of growth depends upon the magnitude of the applied stress, the length of time over which the stress is applied, and the original size of the flaw. In Appendix 1, some limited experimental data are presented on the subject of crack growth in optical glass. Also, an equation is derived in order to compute an appropriate estimate of damage.

## The Drop Ball Test

The drop ball test is purported to be a proof test; i.e., all lenses which pass the test may be sold. However, it was found that, during the drop ball test, both surfaces of the lens are subjected to extremely localized tensile stresses 4/; i.e., the magnitude of the stress drops off very sharply with distance from the impact point. Therefore, a lens which has potentially hazardous flaws will be identified (by fracturing in the drop ball test) only if one of these flaws happens to be relatively near the impact point. When individual lenses are repeatedly subjected to the drop ball test, they typically sustain many impacts before fracturing 5/. This led to the formulation of the "search theory" of impact testing - the ball is searching for a weak spot on the lens (where there exists a sufficiently severe surface flaw).

The same difficulty arises in the ability of the drop ball test to detect potentially hazardous edge flaws. For round lenses subjected to slightly off-center impacts, the tensile stress at the edge differs, from one point to another, by about thirty percent. This difference is large enough to make the search theory applicable for the failures as well 6/. For lenses with asymmetrical shapes, differences in the edge stress as large as 250% have been observed.

According to the FDA regulation 2/, all lenses must be capable of passing the drop ball test. However, it is now clear that impact resistance cannot be verified on the basis of a single impact. Essentially, only a small area of each lens is sampled in the drop ball test. The absence of potentially hazardous flaws is verified for only this small area.

The implication that the drop ball test can be interpreted as a sampling test that insures a minimum level of overall quality must be resisted. This is because no limits are set for the tolerable amount of breakage*. For example, a laboratory which breaks five percent of its lenses (in the drop ball test) produces lenses with an overall quality (in terms of the number of "bad" flaws) which is five times worse than the laboratory which only breaks one percent. As any lens which does not break can be sold, no minimum level of quality can be attributed to it.

A further difficulty with the drop ball test is that the magnitude of the peak surface stresses is very high. Often, relatively innocuous flaws will initiate fracture 7/. Therefore, not all broken lenses were necessarily bad.

The usefulness of the drop ball test is that a laboratory is likely to take measures to minimize the amount of broken lenses. However, the difficulty with enforcing the regulation has led to the suspicion that laboratories with large amounts of breakage may often just suspend the test.

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*It has been shown that the percentage of broken lenses, for a group of identical lenses, is nearly proportional to the number of "bad" flaws per lens 7/. Therefore, the percent of broken lenses could be taken as a measure of the overall quality of the lenses in the group (see section on Sampling Tests in this report).

The possibility that the drop ball test causes damage to lenses must also be investigated. A parameter which measures degradation in drop ball testing is derived in Appendix 1. For surface flaws, the strength degradation is on the order of 1% beneath the impact point. Because the stress drops off so sharply with distance, the average degradation over the entire lens' surface is several orders of magnitude less. Further, it is unlikely that a second impact will coincide with the first; therefore, in terms of a decreased ability to withstand a second impact, degradation is negligible. For edge flaws, degradations are on the order of 0.1% or less.

Often, when high power, thick lenses are drop ball tested, small ring-type fractures can be observed on the impacting surface. As these do not cause catastrophic failure of the lens, the lens has technically passed the test, However, the lens is no longer suitable for sale. Thus, many laboratories insert the lens in a plastic bag before administering the test. It has been suggested that this practice may denigrate the intended purpose of the test 8/. However, we have found that there is a negligible decrease in the ability to detect lenses with "bad" flaws when the plastic bag is used 7/; i.e., the presence of the plastic bag does not change the fact that very few of the bad lenses are detected. On the other hand, the percentage of broken lenses does, of course, decrease. If the drop ball test were to be used as a measure of overall quality, the effect of the plastic bag would have to be taken into account.

## Alternative Proof Tests

One means of eliminating the deficiencies in the drop ball test is to find a method by which any lens containing a potentially hazardous flaw can be identified. This would involve inspecting the entire lens. Early in the program, we investigated the feasibility of nondestructive inspection techniques in which no stress (or a very low level stress) was applied to the lens. None of the standard NDT procedures (e.g., acoustic emission, dye penetrant, ultrasonics, x-ray diffraction) appeared to be suitable for our purposes.

The remaining alternative is to develop a procedure in which nearly uniform tensile stresses can be applied to large amounts of the surface and edges. Two possibilities were investigated: (1) a static load test, and (2) a thermal shock test. Both will be discussed in turn.

In a static load test, a loading configuration is designed for the purpose of producing uniform stresses over a large surface area, and the load is slowly applied to the lens. One restriction is that the stress at the edge must also be relatively uniform and at a lower level than the surface stress (because the edge flaws are so much more severe). The ease with which the load can be applied must also be considered. The resulting stresses from several types of loading configurations were calculated with the aid of a finite element computer analysis*.

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*This computer study, sponsored by the Optical Manufacturers' Association, was performed by R.A. Mitchell, R.M. Wooley and S. Baker of the Engineering Mechanics Section at NBS. The finished product of this investigation, a computer code which evaluates the stress and displacement distribution at all points of a statically loaded lens, was presented to the sponsor.

Concentric ring loading, which had been used successfully for circular disks 9/, proved to be the most promising configuration*. For a fixed support radius, an increase in the load radius (to increase the stressed area) leads to a decrease in the uniformity of the stress distribution and an increase in the edge-to-center stress ratio. For the load radius fixed, an increase in the support radius does not seriously affect the uniformity, but does lead to some decrease in the edge-to-center stress ratio. The values 7 mm and 13 mm, for the load and support radii, respectively, proved to be a reasonable compromise among the constraints. This configuration was tested in the laboratory, with lenses which were instrumented with strain gages, and the agreement with the analytical model was satisfactory.

There are several difficulties associated with the use of a concentric ring apparatus as a proof test for ophthalmic lenses:

1. While the uniformly stressed area in this test is large compared to the drop ball test, it is still small compared to the total surface area of the lens.

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*Other configurations were also investigated: a uniform pressure drop across the lens did not produce as uniform a stress distribution; a second loading ring improved the uniformity of the stress distribution, but the experimental duplication of this configuration was extremely difficult; this was also the problem when the lens was ring loaded while resting on an elastic foundation.

2. The solutions are only valid for axisymmetric lens geometries. Lenses having non-round shapes, or lenses with multifocal segments or cylinders, would not exhibit the same uniformity in the stress distribution.
3. The required load levels are very high (on the order of several thousand newtons) and would vary significantly from one lens power to another (even for symmetric shapes).
4. The high load levels and the necessity for accurate positioning of the lens make this a very difficult test to administer at the optical shop level.

Thermal shock tests have been in widespread use as a tool in crack growth studies of glass specimens. In this procedure, a lens is first heated and then rapidly immersed in a cold bath. Tensile stresses, which are roughly proportional to the temperature difference, build up quickly at all points on the surface and edge. To optimize heat transfer rates, water has been used as the cold bath fluid 10/. This method has already been used successfully with ophthalmic lenses in a study of edge quality; groups of lenses were ranked by comparing the amounts of breakage as a function of the temperature drop 16/.

However, in using the thermal shock method as a test for surface quality, precautions must be taken to insulate the edge. Otherwise, as the most severe flaws are at the edge, all fractures will initiate there. We have built and tested such an apparatus (sketched in figure 1), but its use as a proof test would introduce several difficulties:

(1) it requires modification when the lens geometry is changed, (2) it reduces the tested area, and (3) a separate thermal shock test would be required for the edge.

Other difficulties with thermal shock testing are: (1) some evidence of warping was noted in cases where no fracture was observed, and (2) care must be exercised in maintaining oven and water bath temperatures at the proper levels.

The most serious objection to both of the above proof tests is that the amount of lens damage is significantly greater than in the drop ball test. This is partly because the time duration for applying the load is much longer. Concerning surface degradation, a case can be made for testing at a lower stress level than the maximum in the drop ball test; this can compensate for the increase in the time duration. However, the edge stresses in the drop ball test are already so low that no further decrease seems advisable. Even if the stresses could be applied in .02 seconds*, the strength degradation for edge flaws, in the concentric ring proof test, would be nearly one hundred percent (see Appendix 1). This amount of degradation cannot be tolerated.

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*It is doubtful that the stresses could be applied so quickly in a static load test without a significant increase in cost. Times of this duration may not be inconceivable if thermal shock methods are used. However, because the stresses are applied in a water environment, crack propagation velocities (and hence the degradation) are an order of magnitude higher 11/.

## Sampling Tests

As proof testing does not appear to be an entirely satisfactory alternative to the drop ball test, we turn our attention to the remaining alternative: a sampling test to insure that at least the overall quality of lens production is above some minimum level.

The term "overall quality" must first be defined with respect to impact resistance. A list of parameters that affect impact resistance is presented in Table 1. The likelihood of fracture depends upon both the flaw distribution and the applied stresses. An optical laboratory has little or no control over the second set of parameters in Table 1 (lens geometry), which are usually determined by the customer. "Overall quality" is thus determined by how well a particular laboratory can control those parameters which affect the flaw distribution.

Consider a hypothetical case where a laboratory produces lenses of only one geometry. That is, the variables affecting the stress distribution are fixed. The amount of breakage (measured by the percent of lenses broken) in the drop ball test (or any stress test) can be related to the flaw distribution 7/. The flaw distribution can be identified by the number of "bad" flaws per lens 7/. The overall quality is then maintained by keeping the number of bad flaws per lens to a minimum. In terms of lens breakage, the percentage broken should not exceed some fixed level.

However, each laboratory produces many different lens geometries, and this introduces an entirely new set of variables. That is, there is a distribution of lens geometries, and it is likely that this distribution varies among laboratories. There exists the possibility that the effect of this lens geometry distribution may conceal (or greatly distort) the relationship between the percentage broken and the flaw distribution*. This is the major difficulty with using the present drop ball procedure as a test for overall quality (say, by merely imposing a limit on the percentage broken).

To eliminate these deficiencies, we consider the possibility of sampling with "coupon" lenses. Coupon lenses have fixed geometries of some convenient configuration. As the geometries are fixed, the stress distribution can be estimated and a relationship between the percentage broken and the number of bad flaws per lens (for both edge and surface flaws) can be established. The overall quality of lenses from different laboratories can then be compared.

The obvious objection to such a procedure is that the lenses which constitute the sample are different from those which are being produced for sale. Typical sampling procedures 12/&13/ assume that the products being inspected are nominally identical. The sample is then chosen randomly from the finished products. This procedure is certainly not applicable to the production of ophthalmic lenses, where each finished product is different.

Consider the case of a one-man laboratory with only one piece of equipment for each of the processes discussed in Table 1 (i.e., one grinder, one polisher, one edger, one strengthening unit). As discussed earlier, the introduction of flaws into the surface or edge appears to be a random process. Because the equipment is fixed, we assume that the number of surface flaws

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*For example, the amount of breakage for typical -2 diopter lenses is over twice as great as for typical +2 diopter lenses when the flaw distribution is assumed fixed. This is one of the results of the finite element computer study.

introduced should depend only on the amount of surface area processed. Similarly, the number of edge flaws introduced should depend only on the amount of edge length processed. We assume that these flaw distributions can be satisfactorily described after some finite amounts of surface area and edge length have been processed, regardless of what lens geometries are being produced. Therefore, a batch should not be defined in terms of a number of finished lenses but in terms of the amounts of surface area and edge length processed.

For large laboratories, batches must be defined separately for each combination of the parameters that affect the flaw distribution (Table 1). The coupon lenses are processed at predetermined intervals during the production of each batch. Each coupon lens then comprises a sample of surface area and edge length. Tests are conducted on them to assess the overall quality of the entire batch.

The establishment of criteria for determining the amounts of surface area and edge length which constitute a batch is outside the scope of this report. However, a general guideline can be suggested: the surface area and edge length of a batch should be large compared to sizes required to describe the flaw distribution, but not so large that significant changes in the equipment have taken place.

## An Example

In this section, an example is presented on the use of coupon lenses in a sampling test for the overall quality of a batch of ophthalmic lenses. In order to make the results quantitative, particular safety criteria and coupon lens geometry are considered. It should be understood that this example is for illustrative purposes and that analogous procedures can be used for any safety criteria and coupon lens geometry.

To set safety criteria for ophthalmic lenses, one must first choose bad flaw levels for surface and edge flaws. We have already discussed the idea of categorizing flaws by the critical tensile stress required for fracture initiation 7/. At the bad flaw level, s*, all flaws with critical tensile stresses less than or equal to s* are considered bad. For edge flaws, we will designate the bad flaw level by $s_E$*.

For a given flaw distribution, the number of bad surface flaws per lens* can be represented by the function F(s*) 7/; for edge flaws, $F_E(s_E^*)$ 6/. The overall quality of a group of lenses is considered acceptable if the number of bad flaws per lens is less than or equal to some designated amount:

$$\begin{aligned} &\text{surface:} \quad F(s^*) \leq N \\ &\text{edge:} \quad F_E(s_E^*) \leq N_E \end{aligned} \tag{1}$$

In this example, we will use the following values:

$$\begin{aligned} s^* &= 138 \text{ MN/m}^2 \quad (20000 \text{ psi}) \\ s_E^* &= 89 \text{ MN/m}^2 \quad (13000 \text{ psi}) \\ N &= N_E = 0.05 \text{ bad flaws per lens} \end{aligned} \tag{2}$$

The value for s* was used for illustrative purposes in a previous paper 7/. This level was considered to be sufficiently high to insure that lenses will be properly strengthened. The value chosen for $s_E$* is also arbitrary. It happens to be the highest edge stress which was measured in some earlier experiments 6/.

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*Actually, as discussed in the previous section, the number of bad flaws per unit area would be a more appropriate parameter. However, as the coupon lenses all have the same geometry, the area per lens is fixed, and the two quantities differ by a constant factor.

For coupon lenses, we will use round, plano lenses, 48 mm in diameter, with center thickness, 2.2 mm. These lenses were chosen because the resulting stress distribution during impact has been experimentally obtained 4/. Any lens configuration will do, as long as the stress distribution is known.

The relationship between the expected percentage of broken coupon lenses in the drop ball test and the number of bad surface flaws per lens is as follows 7/:

$$P(s_{DBT}) \quad \frac{(k+1)F(s^*)}{(s^* - s_o)^{k+1}} \; s_{DBT}^{k+1} \int_{Zo}^{1} (Z - Z_o)^{k+1} \; G(Z)dZ \qquad (3)$$

where $s_o$ and k are parameters of the flaw distribution function, $s_{DBT}$ is the maximum stress in the drop ball test ($s_{DBT}$ = 350 $MN/m^2$, 50000 psi), and $Z_o = s_o/s_{DBT}$. G (Z) is a function that depends only on the stress distribution and is considered fixed for a given geometry of the coupon lens 7/. Substituting the maximum allowable number of bad surface flaws, N, for F(s*), we obtain the maximum allowable value for the expected percentage of broken lenses, $P(s_{DBT})$. More breakage than this indicates that the number of bad flaws per lens in the batch is too high.

Before a numerical value can be obtained for $P(s_{DBT})$, values must be chosen for the flaw distribution parameters $s_o$ and k. In particular, $s_o$ is the critical stress of the most severe flaw (lowest critical stress). It follows from equation (3) that the choice, $s_o = 0$, leads to the smallest value for $P(s_{DBT})$, for all other parameters fixed. As this is the level at which the rejection/acceptance decision is made, the choice, $s_o = 0$, is thus conservative. The value, $k = 3.8$, has been used previously to represent some experimental data 7/. Also it has been shown that the number of bad flaws per lens is not particularly sensitive to this parameter 7/. So, from equation (3), using the values $s_o = 0$ and $k = 3.8$, and the stress distribution G(Z) from a representative lens, we obtain:

$$P(s_{DBT}) = 1\%$$

An analogous procedure can be repeated for edge flaws (Appendix 2.1):

$$P(s^E_{DBT}) = 2\%$$

For the safety criteria set in (1), a group of coupon lenses with less than 1% breakage due to surface flaws and 2% breakage due to edge flaws is considered to represent an acceptable batch.

In figure 2, an outline of the relationships, which are discussed in this section, is presented. Equation (3) is thus the relationship between box A (the safety criteria) and box B (the maximum allowable percentage of broken lenses).

An essentially unmeasureable parameter, the number of bad flaws per lens, has now been related to a readily measureable parameter, the percentage of broken coupon lenses. By testing a sample of coupon lenses, it is desired to infer whether the percentage of broken lenses in a large population of coupon lenses is less than $P(s_{DBT})$. If this inference is made, it can be stated that the number of bad flaws per lens is less than N. Then, because the flaw distribution is assumed to be independent of lens geometry, it can also be inferred that the number of bad flaws per lens in the general population is also less than N.

For a given confidence limit, the number of coupon lenses required for testing decreases sharply as $P(s_{DBT})$ increases 14/. Without changing the allowable number of bad flaws per lens, $P(s_{DBT})$ can be increased by modifying the test method (say, by changing the stress distribution, $G(Z)$, in equation (3)). Thus, if an alternate test method is used, in which the tensile stresses are more severe or are applied over a larger part of the lens, the percentage of broken coupon lenses will increase, and the number of coupon lenses required for testing will be reduced.

For this example, we will consider a similar test to that presently used: a drop ball test with a 7/8-inch (22 mm) diameter steel ball. One advantage of such a test is that laboratories would not have to purchase new equipment. The allowable percentage of broken lenses in this new test, $P(s_{new})$, can be related to $P(s_{DBT})$. This relationship is derived in Appendix 2.2 and connects boxes B and C in figure 2. Again, if $s_o$ is set equal to zero, this percentage will be a minimum and thus conservative. For our example, the calculated values are:

$$P(s_{NEW}) = 10\%$$
$$P(s^{E}_{NEW}) = 10\% \tag{4}$$

The number of coupon lenses required to verify these percentages of broken lenses is correspondingly reduced.

One other relationship may be of interest (see boxes D and B of figure 2). For a fixed flaw distribution, the percentage of broken lenses in the drop ball test can be computed for other lens geometries. Such calculations would follow straightforwardly from the finite element computer program referred to earlier. An average percentage broken, $\bar{P}(s_{DBT})$, can then be formed and this average compared to $P(s_{DBT})$. If the geometries are selected carefully, the average, $\bar{P}(s_{DBT})$, can be considered an estimate for the overall amount of breakage in a laboratory. Of course it may be necessary that the averaging process vary among laboratories. This relationship also allows for a different, and possibly more convenient, approach in determining the rejection limits for the sampling test with coupon lenses. Referring to figure 2, the path $D \rightarrow B \rightarrow C$ can be used instead of $A \rightarrow B \rightarrow C$. That is, a limit is first set on the overall percentage broken that is allowable. As records of drop ball testing have been mandatory, there should be plenty of data on which to base this limit. This limit is then a reflection of the present state-of-the-art and can be modified if new technologies are developed. The corresponding percentages of broken coupon lenses in the drop ball test and the new sampling test then follow from the relations $D \rightarrow B$ and $B \rightarrow C$ (figure 2), respectively. Using the value $s_o = 0$, the resulting limits are conservative. This approach is desirable because the complicated (and somewhat arbitrary) decisions, regarding bad flaw levels and the tolerable amount of bad flaws, are avoided.

## Summary

The results of the research associate program indicate that it is desirable to replace the drop ball test with a sampling procedure from which meaningful information on lens quality can be obtained. We have discussed some aspects of the design of a sampling plan in which the overall quality of a laboratory's lenses is monitored by regularly testing a set of coupon lenses. Several methods for determining acceptance/rejection criteria (e.g., based on the number of tolerable bad flaws or on the present state-of-the-art) have been suggested. Details for an actual sampling plan (which must also address the questions of when to produce and test coupon lenses, what steps to take if rejection is indicated, and how to enforce the plan) are deferred to such time when a rigorous statistical evaluation can be performed.

The sampling procedure suggested in this report is intended as a guide. Many modifications to this procedure can be imagined. For example, it is possible that the manufacturer could verify the surface quality of lens blanks (by testing coupon blanks, say). Then the optical laboratory can be assured that the breakage it sustains is not due to processes beyond its control.

Whatever direction the final sampling plan may take, some testing may be necessary to verify certain assumptions. For example, in the suggested approach of this report, a verification is required to confirm that the flaw distribution is independent of lens geometry (if not, difficulties can be circumvented by testing a worst case geometry).

The proof test methods discussed in this report (concentric ring static load and thermal shock) are not suitable for verifying the impact resistance of individual ophthalmic lenses. However, they may be of use to the optical industry as a research tool; i.e. these tests would allow for a more efficient determination of the effectiveness of new materials or strengthening methods, if they are introduced.

It should be reemphasized, before closing, that the focus of this report, and the entire program, has been on glass ophthalmic lenses. Modifications would be required before the proposed sampling test could be adopted for plastic lenses.

At this point, the NBS/OMA Research Associate Program terminates. Until now, we have been concerned with the mechanical dynamics of impact resistance and the drop ball test in order to understand the limitations of the present test and to make recommendations for improving it. The refinement of a new testing procedure, such as one suggested in this report, lies in area of applied statistics.

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## Appendix 1

The stress intensity factor, K, is often regarded as the best measure of crack severity.

$$K = Y_0 s \sqrt{a} \tag{1.1}$$

where s is the applied tensile stress normal to the plane of the crack, a is the depth of the crack, and $Y_0$ is a geometrical parameter 15/. An experiment was performed to determine the relationship between the stress intensity factor and the crack velocity, V, for optical glass. The results are shown in figure 3.* According to Evans and Wiederhorn 15/, crack growth is mostly controlled by the low velocity region of the curve where the relationship between V and K can be described by

$$V = AK^n . \tag{1.2}$$

The exponent, n, was determined by least squares fit to be 20.4. Cracks grow catastrophically when the stress intensity factor reaches a critical value, $K_c$, often estimated by extrapolating the high velocity portion of the V-K curve to $10^{-1}$ m/sec. For optical glass then

$$K_c = 0.84 \ MN/m^{3/2} . \tag{1.3}$$

If a loading stress s is applied for a time $\Delta t$, a typical crack will grow from an initial depth $a_i$ to a new depth $a_f$. From 1.1 the corresponding stress intensity factors $K_i$ and $K_f$, can be calculated. The relationship between $K_i$ and $K_f$ is found 15/ by integrating equation 1.2:

$$K_i^{2-n} - K_f^{2-n} = \frac{\Delta t}{2} (n-2) A \, s^2 Y_o^2 \tag{1.4}$$

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* These measurements were performed by Dr. Sheldon Wiederhorn, Physical Properties Section, NBS.

Then from 1.4, using 1.1 and 1.2:

$$\frac{K_i}{K_f} = \left[ 1 - \frac{n-2}{2} \Delta t \frac{V_i}{a_i} \right]^{\frac{1}{n-2}} \qquad (1.5)$$

If $s_i$ and $s_f$ are the stresses required for failure (i.e. for $K = K_c$ from 1.3), before and after crack growth, then

$$\frac{s_f}{s_i} = \frac{K_i}{K_f} \qquad (1.6)$$

The percentage decrease in the stress required for fracture is an appropriate measure of strength degradation:

$$D = \frac{s_i - s_f}{s_i} = 1 - \left[ 1 - \frac{n-2}{2} \Delta t \frac{V_i}{a_i} \right]^{\frac{1}{n-2}} \qquad (1.7)$$

Order of magnitude estimates for the applied stresses on the surface and edge of the lens during the drop ball test are $3.5 \times 10^8$ N/m$^2$ and $0.7 \times 10^8$ N/m$^2$, respectively 4/. The depths of cracks causing failure are then obtained from equation 1.1* with $K = K_c$:

surface, $a_s$ = 1.44 micron; edge, $a_E$ = 36 microns

For the purpose of illustration we calculate the strength degradation for cracks which are initially half as large as those causing failure:

$a_{si}$ = 0.72 micron; $a_{Ei}$ = 18 microns

From 1.1, the stress intensity factor for both these cracks is about 0.6 MN/m$^{3/2}$ for which the velocity (from figure 3) is about $10^{-4}$ m/sec. The duration of contact is about 0.2 msec 4/. Then from 1.7

$D_s = 10^{-2}$, $D_E = 5 \times 10^{-4}$

---

*Using $Y_0 = 2$ for a crack which can idealized as a segment of an ellipse 7/.

If the duration were increased by two orders of magnitude, to 20 msec, the same edge flaw would grow to 36 microns and failure would be imminent. The corresponding degradation would be nearly 100%.

## Appendix 2.1

For a round lens, a reasonable first approximation is to assume that the applied stress $s^E_{DBT}$ is uniform at the edge. Let $F_E(s^E_{DBT})$ denote the fraction of edge flaws with critical stresses less than or equal to $s^E_{DBT}$. If the edge flaws can be represented by a Weibull type distribution 7/, then

$$F_E(s_E) = \frac{C}{k_E+1}(s_E - s^E_0)^{k_E+1} \qquad (2.1.1)$$

Therefore $$F_E(s^E_{DBT}) = F_E(s_E^*)\left[\frac{s^E_{DBT} - s^E}{s_E^* - s^E_0}\right]^{k_E + 1} \qquad (2.1.2)$$

The percent of lenses expected to break due to edge failures in the drop ball test is 7/:

$$P(s^E_{DBT}) = 1 - \exp\left[F_E(s^E_{DBT})\right] \qquad (2.1.3)$$

It remains to determine the parameter, $k_E$, for edge flaws. Consider an experiment in which groups of lenses are subjected to thermal shock-all lenses which break have failures originating at the edge. The percentage of broken lenses is recorded as a function of the temperature difference, $\Delta T$. As $\Delta T$ increases the number of broken lenses increases. The applied stress at the edge is proportional to the temperature difference:

$$s_E = \alpha\Delta T,\ s^E_0 = \alpha\Delta T_0 \qquad (2.1.4)$$

$F_E$ is determined from the percent broken data by equation 2.1.2. Then from 2.1.1 and 2.1.4:

$$\ln F_E = b + (k_E + 1) \ln (\Delta T - \Delta T_0) \qquad (2.1.5)$$

Where $b = \ln \dfrac{C^{(k_E + 1)}}{k_E + 1}$

In figure 4, $F_E$ is plotted as a function of $\Delta T - \Delta T_0$ on log-log paper*. The slope is then $k_E + 1$. From the figure $k_E = 2.2$. $P(s^E_{DBT})$ then follows from 2.1.1 and 2.1.2.

## Appendix 2.2

For the drop ball test, the following relationship between the stress on the lens and the input kinetic energy, K, was experimentally verified 4/:

$$\frac{s_{NEW}}{s_{DBT}} = \left[\frac{K_{NEW}}{K_{DBT}}\right]^{\frac{1}{2}}$$

Now K is proportional to the mass of the impacting steel ball, the mass is proportional to the volume and the volume is proportional to the cube of the diameter. Therefore,

$$\frac{s_{NEW}}{s_{DBT}} = \left[\frac{D_{NEW}}{D_{DBT}}\right]^{\frac{3}{2}} = \left[\frac{7/8 \text{ in.}}{5/8 \text{ in.}}\right]^{\frac{3}{2}} = 1.65$$

From equation (3)

$$\frac{P(s_{NEW})}{P(s_{DBT})} = \left[\frac{s_{NEW}}{s_{DBT}}\right]^{k+1} = (1.65)^{4.8} \cong 10$$

For edge flaws $\dfrac{P(s^E_{NEW})}{P(s^E_{DBT})} = (1.65)^{3.2} \cong 5$

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*From OWA study 16/.

Table 1. Parameters that Affect Impact Resistance

Parameters that Affect the Flaw Distribution

1. Quality of grinding and polishing (surface flaws)

2. Quality of edging (edge flaws)

3. Quality of strengthening (surface and edge flaws)

   Also changes in the specific piece of equipment and/or the operator are also likely to affect the flaw distribution

Parameters that Affect the Stress Distribution

1. Thickness

2. Power

3. Base curvature

4. Shape

   These parameters determine the stress distribution for a given impact or static loading condition. The presence of cylindrical power and/or multifocal segments would also affect the stress distribution.

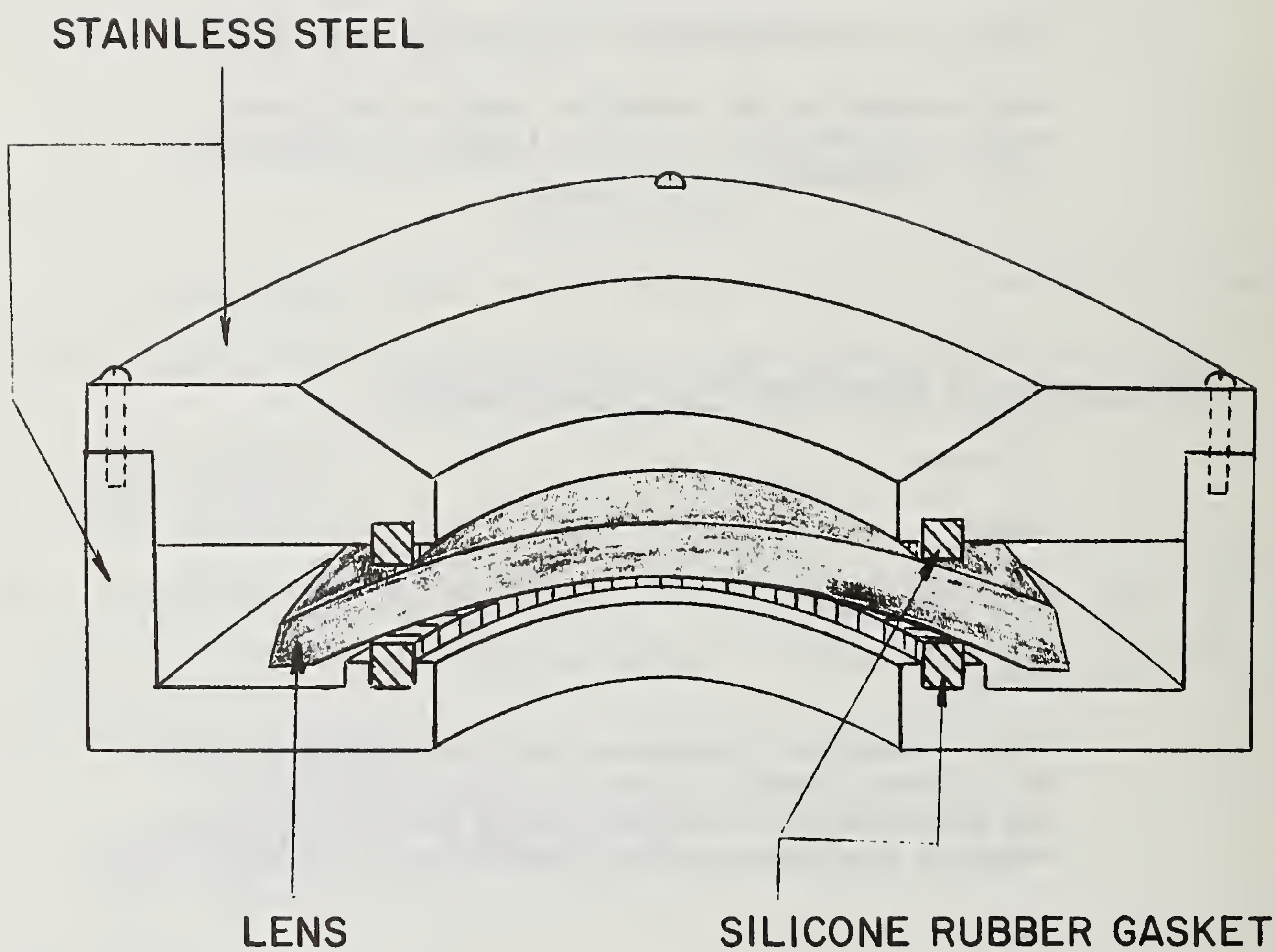


Figure 1. Schematic Drawing of Apparatus Used To Insulate the Lens Edge in Thermal Shock Tests.

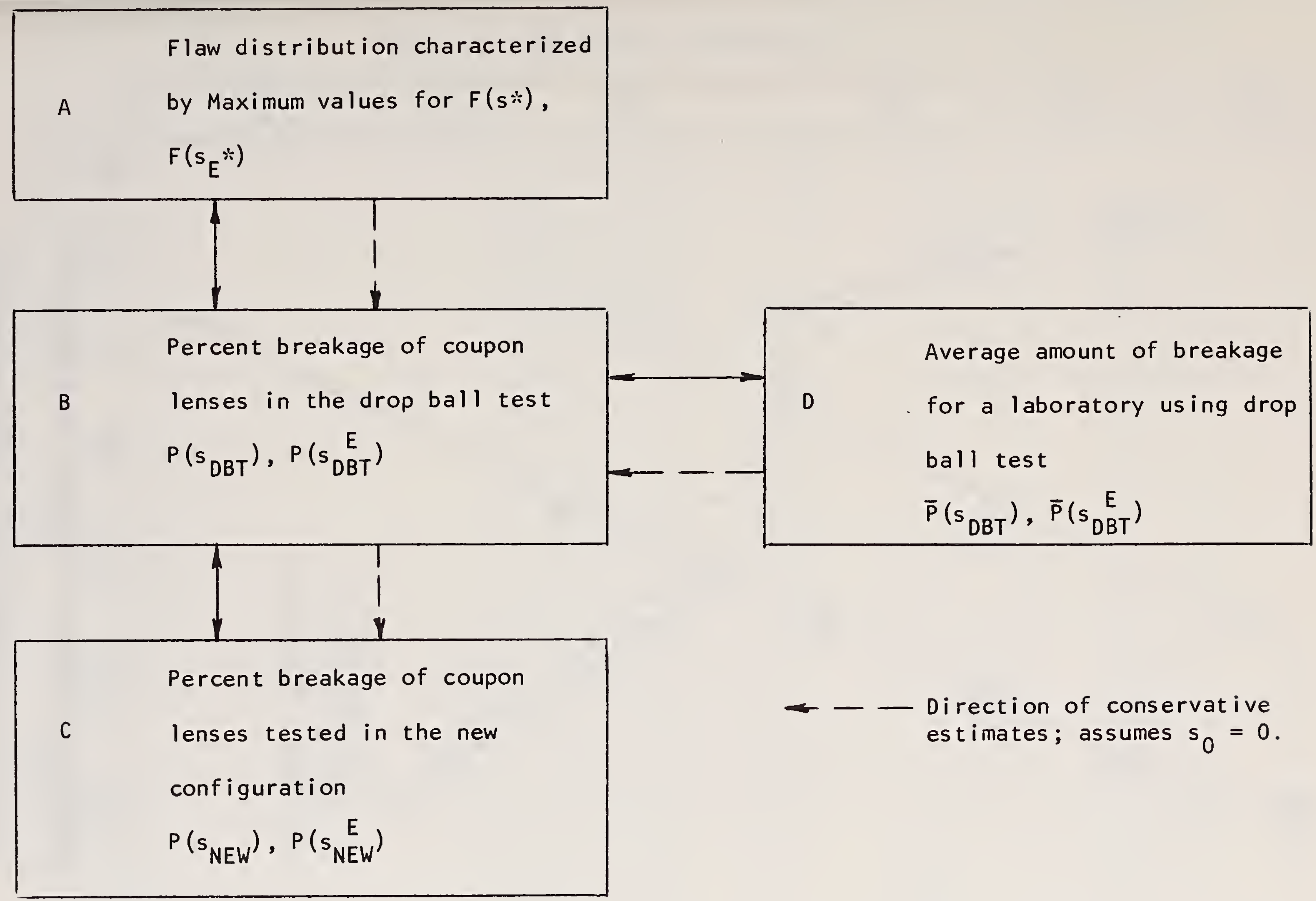


Figure 2. Relationships between lens breakage and the flaw distribution

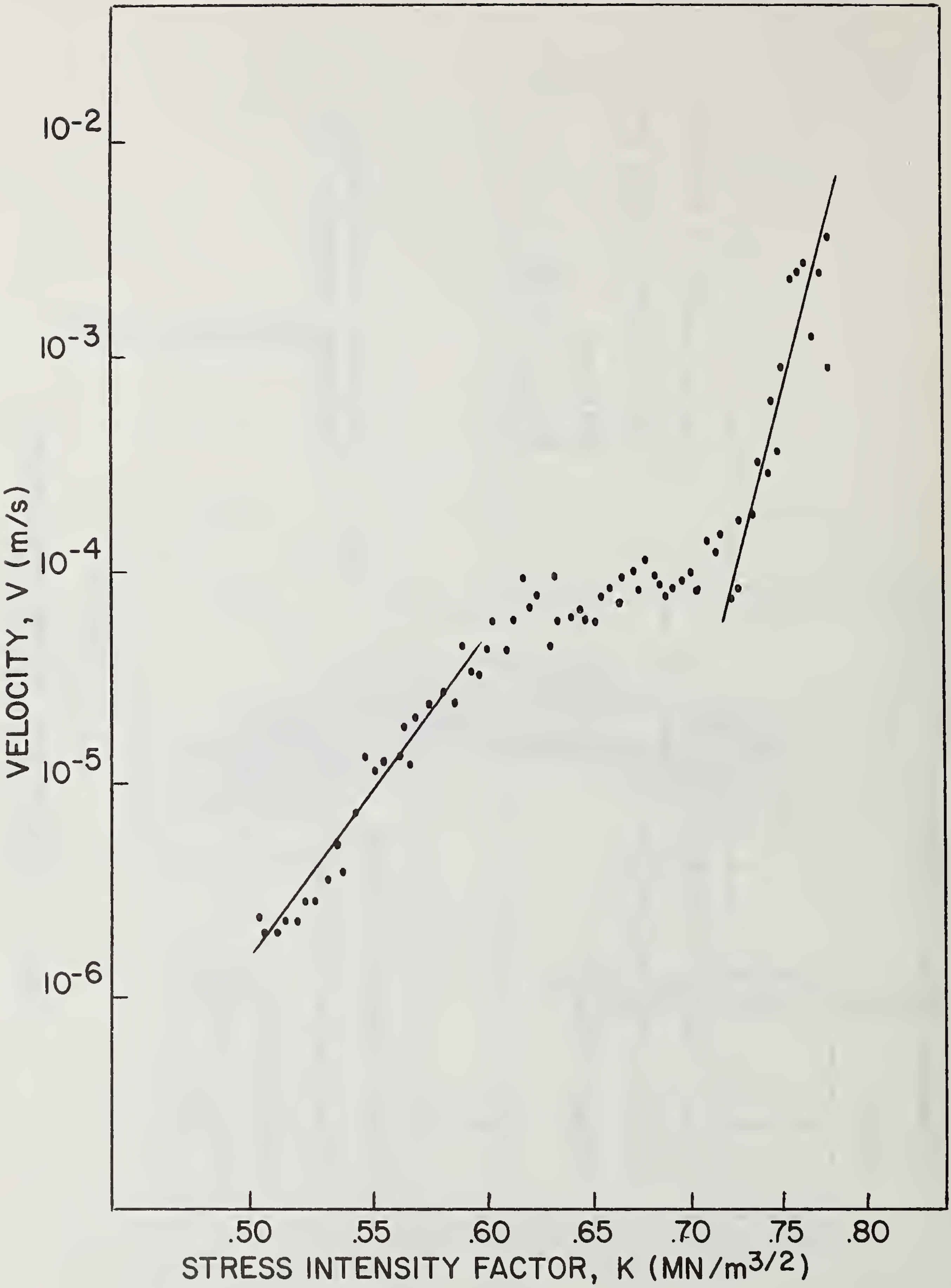


Figure 3. Crack Propagation in Optical Glass

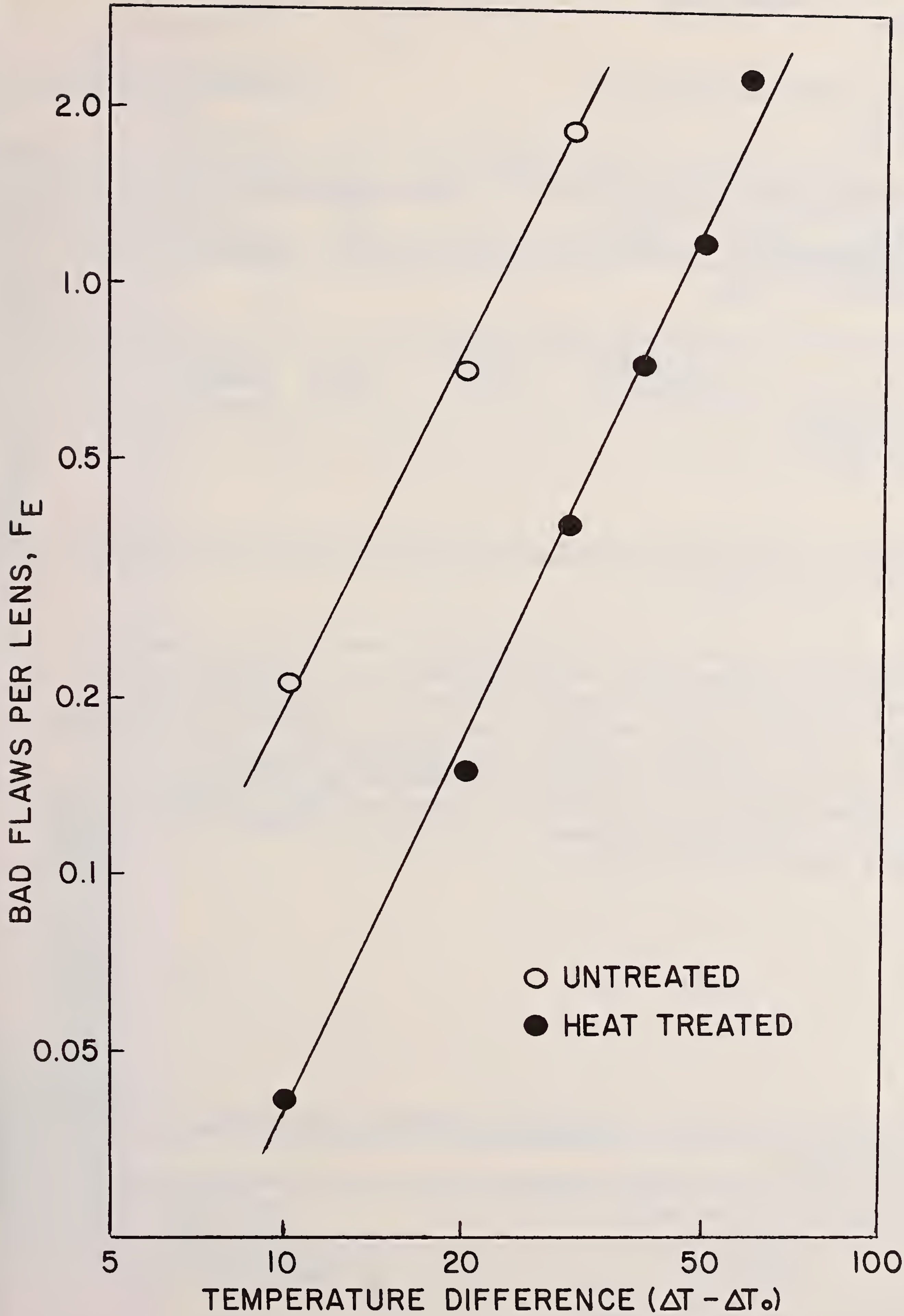


Figure 4. Results of Thermal Shock Tests 16/. $F_E$ Inferred From Breakage Data (Equation 2.1.3).

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The principal findings of the Optical Manufacturers Association's Research Associate Program are summarized. The limitations of the present drop ball test for impact resistance are discussed. Essentially, only a small part of the lens surface and a small part of the edge are subjected to sufficiently high stresses. It is therefore desirable to replace the drop ball test with a sampling procedure from which meaningful information on lens quality can be obtained. Some aspects of the design of a sampling plan, in which the overall quality of a laboratory's lenses is monitored by periodically testing a set of coupon lenses, are discussed.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Drop ball test; impact resistance; ophthalmic lens; proof testing; research associate program; sampling test.

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