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BOTTLE BREAKAGE—CAUSES AND TYPES OF FRACTURES*

Outline Study Course on Mechanical Properties of Glassware with Particular Reference to Glass Containers

By F. W. Preston

I. General Principles†

In various scientific papers, the writer has discussed the breaking of glass and glass articles, in most cases paying particular attention to the arrangement of the various cracks into recognizable patterns and to the appearance of the fractured edges. These papers are the groundwork of what follows, but we have learned a great many details since the scientific principles were laid down. These details are often useful in determining whether a bottle was broken the way a complainant in a lawsuit says it was or whether the case contains elements of deceit. They may also be of use in guiding the design and manufacture of bottles; in fact, they have already proved useful.

Here we are attempting to give an outline introduction to the subject for men who may be studying it for the first time. While it is now possible for a beginner to learn in a few months what it took us years to piece slowly together, no one should get the impression that after reading this document, a man will be able to recognize, instantly, fraudulent cases or even to diagnose, beyond the possibility of error, exactly what happened to a broken bottle to break it. Only patient examination of many fractures will enable him to do that.

There are several simple points that an investigator must understand.

The first is that a broken bottle is not a mass of meaningless fragments. The cracks are a definite response to the forces producing them. The connection may be complex, but it is definite, and the investigator must have confidence that with sufficient patience, study of the specimen, and attempts to duplicate it he may succeed in attributing the correct meaning to them and in ruling out other meanings or guesses.

The second point is that, while the actual process of making the glass break may take many forms—internal pressure, external pressure, an impact, a sudden change of temperature, poor annealing, cords; fatigue—a crack has only one *immediate* cause, *viz.*, mechanical stress. Further, this stress is always a tensile stress, and it is always at right angles to the crack. Compressive stresses and shear stresses do not produce cracks, except insofar as they develop tensions incidentally. A "tension" is a stretching or attempt to pull further apart the "fibers," or better, the "molecules" of the glass. It follows that, because in practice "simple" tensions are never encountered but are invariably mixed up in a complex stress system in which multiple tensions (tensions in several directions), compressions, and shear stresses are involved, an investigator should devote some time to familiarizing himself with the elementary theory of elasticity. For this purpose, the simplified treatment usually fed to engineers in college under the title of "strength of materials," usually suffices. The important thing is that the investigator must set out to acquire a visualization of stress systems as a whole. Until he does that, he is easily misled.

The third point is that, while in most cases of breakage the complete fracturing of the bottle takes place in something like one-thousandth part of a second, all the cracks are not formed simultaneously. Except in circumstances which we shall mention later, there is a single origin for all the fractures, and the various fissures are propagated through the bottle from this point. Thus some parts are cracked or fractured ahead of other parts, and usually the direction in which the fracture was traveling is clearly indicated on the fracture surface. One of the first things an investigator has to learn is to trace fractures back toward the origin. When the origin has once been located, the battle is usually half won.

The fourth principle is that we find as a matter of experience that fractures nearly always originate at a surface and not in the interior of the glass mass. In the case of a bottle, for instance, the fracture may originate on the outer or inner surface. It is important to find out which, because that automatically eliminates certain possible causes of breakage.

It will be found as a rule that if the fracture originates on the outside of the bottle it will travel for a great distance, faster on the outer face than on the inner face. Ultimately, it may reverse itself and travel faster on the inner face, owing to a different set of stresses or to the levering action of the internal pressure on cantilevered fragments finally preponderating over the momentary and much more severe stresses of internal pressure or external force. Such a change-over should be noted.

Under certain conditions, particularly impact with small, round, hard objects, the origin may involve two sets of fractures, one starting on the inside and the other on the outside. This should be watched for. The fractures may cross each other as seen from a distance. Fractures crossing each other should be eyed with suspicion and the details should be determined because, obviously, if one fracture goes completely through the thickness of the glass, another can not cross it but must be arrested by it.

Fifthly, it should be pointed out that, on the face of things, fractures may be propagated with different velocities, from zero up to the speed of sound in glass, which is very high. Indeed, it is higher than in steel or nickel, and much higher than in most other metals. The velocity of sound in glass is reported as about 15,000 feet a second (10,000 miles an hour). Recent evidence obtained in Germany by Schardin indicates that the maximum speed of propagation of a crack is about one-third of this, depending on the composition of the glass. At present, it is not obvious what limits the speed to this figure; in fact, we ought not yet be too confident that it is a definite and final physical limit. Schardin believes that a crack always travels at this speed or else "dwells" and is never propagated at any other speed. This matter is still *sub judice,*

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† October 30, 1936. All revisions on each part were made on November 17, 1938.

for on the face of things, cracks can travel continuously at exceedingly slow velocities (see Part IV, Experiment No. 1, p. 7).

We can say, however, with some confidence that Schardin has shown that if a crack in a bottle is a foot long, it could be formed in $^{1}/_{5000}$ part of a second, if it were all formed at maximum speed. In practice, it would seem likely that the peak velocity may be reached for a short part of the time, but on the fractured surface at the end of the experiment, there are features that appear to depend on the violence of the cracking process, which we have hitherto called the "speed" of the fracture. This speed or violence is low at the start, high after the fracture is well started, and slow at the finish. At very slow speeds, the surface is nearly featureless; at moderate speeds, it tends to be ribbed or rippled, as if there were a pulsation propagated in the glass concurrently with the fissure. These pulsations may be likened to ocean "rollers" present when there is a wind (not a gale). Finally, when the speed of propagation becomes very great, a gray, dull surface is produced, which under the microscope proves to be a series of overlapping fissures, also known as "striations."[1] Strictly speaking, these are due to instability of the wave-front, which tends to break up into a number of independent fissures. In a crude way, they may be compared to ocean "combers" or "breakers," when the wind is too great or gusty for the waves to synchronize themselves with it.

"Striations" appear on a large scale, even with moderately rapid fractures, when a well-developed fissure tries to re-orient itself to a changed direction of stress. This usually happens toward the end of a fracture's travel, and it must not be assumed that striations are a sign of great violence. Some violence is implied, but it need not be excessive. The fundamentals involved can be mastered by reading a paper on the "split-wave-front."[2]

We shall take up in more detail various aspects of the foregoing point and consider the ways in which bottles can be broken and the forms the fractures tend to take. The general principles are laid down first, because the forms of fractures are altogether too complicated to be understood in the absence of guiding principles.

II. Examples of Typical Breaks*

We mentioned at the outset that the fragments of a broken bottle are not just an amorphous, meaningless mass, but that they can usually be made to outline the circumstances producing the break.

Every bottle manufacturer knows that a thermal shock fracture, as made in his testing department, does not in the least resemble the cracks from a hydrostatic test. In the thermal shock test, the bottle, though cracked, likely remains in one piece or, at the most, the bottom comes out separately. If the glass is bad or the shock unusually severe, he may get two or three separate pieces, but on a "pressure" test, he usually gets a great many fragments, and these dagger-sharp (not rounded). Most manufacturers would be able to identify a bottle broken by a normal thermal shock and would recognize it as something different from a bottle broken by a blow, but they might be (and usually are) much less able to distinguish between a blow and internal pressure breaks and those due to a blow.

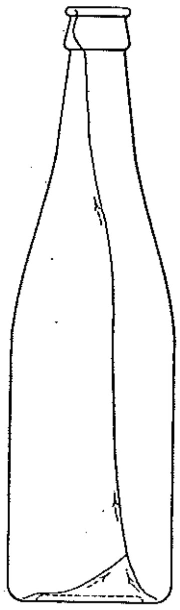

Fig. 1

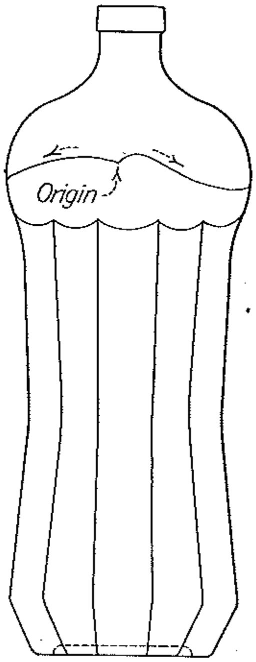

Fig. 2

Fig. 1.—A fairly typical thermal shock crack in an emerald green soda pint, made by quenching in water with an 80° differential. The arrows show the direction of propagation of the crack. The origin is not shown in this figure. Typically, the origin is in the base; often in the baffle mark. In the present instance, the base did not separate completely from the rest of the bottle, and the exact position of the origin was not determined. The crack tends to be very smooth and brightly polished throughout most of its extent, without forks, and striated only where it turns at a flat angle to the face.

Fig. 2.—A thermal shock crack in a 10-sided emerald green siphon bottle. The crack is confined to a circumferential fissure around two-thirds of the shoulder. The origin is a trifle abnormal in showing a sharp change of direction of the external trace; a much slighter change of direction is typical. There is no vertical fissure and no spiral fissure traveling down to the base; there is no crack in the base at all. This is entirely different from typical beers, sodas, etc. The fissure is very smooth and highly polished, and in this case the bottle did not break into two separated parts, though such a result is more usual. Arrows mark directions of propagation. Crack made by quenching in water at 76°F differential.

An earlier paper[3] described some of these phenomena, but we have learned a good deal since those days.

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[1] The term "striation" can mean so many things that it should be used with care or with adequate explanation of the precise meaning; see F. W. Preston, "The Term 'Striation' and Certain Other Terms Used in Glass Technology," *Bull. Amer. Ceram. Soc.*, 18 [1] 12–20 (1939).

[2] F. W. Preston, "Propagation of Fissures in Glass and Other Bodies with Special Reference to the Split-Wave Front," *Jour. Amer. Ceram. Soc.*, 14 [6] 419–27 (1931).

* October 30, 1936.

[3] F. W. Preston, "Form of Cracks in Bottles," *Jour. Amer. Ceram. Soc.*, 15 [3] 171–75 (1932).

The usual effect of heating a bottle in hot water and plunging it into cold, if it produces a crack at all, is to start a crack in the base, more often than not in the baffle mark, which tends to concentrate the stress or represents a "fold" in the "grain" of the bottle. This crack is sometimes invisible, but a subsequent pressure test may show that the strength of the bottle has been ruined none the less, and the pressure break is abnormal in its point of origin. Therefore, bottles that have been given a thermal shock test should not be sent out to the trade unless they have been given a subsequent pressure test to show that the pressure strength is still adequate.

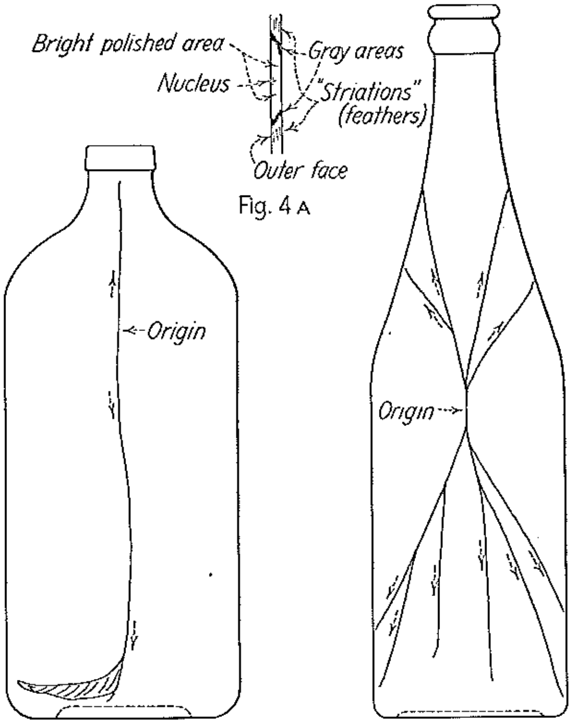

Fig. 4 A

Fig. 3

Fig. 4

FIG. 3.—Thermal shock crack in a cylindrical siphon; origin near the shoulder, at a very slight bruise; main crack vertical, as in typical sodas and beers, but originating at a totally different place.

FIG. 4.—Internal pressure break in typical soda bottle. This bottle was not very strong and broke at a moderate pressure. In consequence, the amount of forking of the cracks is moderate also; when a bottle breaks under high pressure, the number of fissures is vastly greater. The origin is in normal position, on the barrel of the bottle, and normally oriented, *i.e.*, the initial fissure runs straight up and down. It forks at a normal time, *viz.*, just as soon as the bright polished area of the origin gives way to a gray striated structure (shown in Fig. 4*A*, which is a slightly enlarged view of the origin). The nucleus of the origin is some irregularity or bruise on the outer face of the bottle wall, and the origin in its entirety is square to the face of the glass.

Sometimes the crack is visible and is confined to an inch or two of length, extending some distance round the base. Such cracks are unusual, at least in bottle glass, but J. T. Littleton states that they are more frequent in borosilicate glasses.

The usual thermal shock crack extends completely round the base and runs up the side; the bottom may be completely detached and has a low triangular piece on one side (Fig. 1) where the crack meets itself again. The crack that turns upward along the barrel of the bottle usually goes up fairly straight in bottles of typical shape; it may run all the way to the finish, or it may hesitate at the shoulder and either turn over and down or put a wave in its otherwise direct course to the top. The form depends partly on the shape of the bottle and partly on the completeness of immersion of the bottle in the two water tanks, hot and cold.

In the case of siphon bottles, we have recently found that the base is not the vulnerable place; the shoulder is apt to be weaker, particularly in the new stylish, ten-panelled varieties, produced in the first instance in Czechoslovakia. This shoulder weakness in some cases is definitely attributable to the tendency of these bottles to get bruised at the shoulder (the widest diameter), and thermal shock fractures then start from such a bruise as a nucleus (Fig. 2).

In the case of cylindrical siphons, we have found the fracture originating frequently at the shoulder but often enough at bruises at any height along the side (Fig. 3). For some reason, the bases of these bottles are not vulnerable, perhaps owing to favorable stresses left by annealing, perhaps to other circumstances not yet fully worked out. The baffle marks are usually less conspicuous in siphons, and it is these which seem to be the Achilles' heel of the average beverage bottle.

Ordinarily thermal shock fractures do not fork and become multiple fissures. The fracture surfaces are smooth and polished and nearly featureless. There is no gray or mat surface as a rule. The fissure apparently is a slow traveling one. Woodworth feathers or "striations" may be (and usually are) found toward the ends of the fissure, which usually tries to turn over and change its plane.

The fissure is at right angles to the surface of the glass at its point of origin and usually throughout much of its length, particularly on the vertical split; these parts of the fissure are nearly featureless—so much so that the origin is often difficult to locate with certainty.

This description applies only to the case where thermal shock acts alone; necessarily the picture is changed if the bottle is under internal pressure when the thermal shock is administered. In that case, the internal pressure, if of any appreciable amount, takes charge of the explosion after the thermal shock has pulled the trigger.

Let us turn now to a typical "pressure" or hydrostatic break. In a typical bottle, such as a ginger ale or old-style beer bottle, the fracture originates on the outer side of the wall of the barrel part as a short vertical split. It is vertical because the greatest tension is horizontal; it is on the outside[4] because the outer face, blown against an iron mold, is less perfect than the inner face, blown against air.

The origin shows on the fractured surface as a bright polished area, semicircular or rather semi-elliptical in shape, extending nearly through the thickness of the glass

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[4] See Part IX, third paragraph (p. 13), and footnote 22.

and up and down several times as far. It is margined by a gray or mat area; immediately beyond this, rough striations appear, and the fracture forks into several cracks (Fig. 4). Some of these fissures may not go entirely through the thickness of the glass; the outermost do and usually some of the others.

As it is usually quite impossible to arrest the pressure at this stage, the fractures travel completely round the bottle and meet on the far side. The neck is intact, and attached to it is the fan of fissures representing the upper "radiant." The base is typically intact, and attached to it is the lower fan of fissures. The barrel of the bottle may remain in one piece, like a collar, narrow on one side at the origin and wide on the other. More often it is in two large pieces, the collar splitting up the back with a crack which is not perpendicular to the surface. These three or four pieces are a theoretical minimum. In practice, the number of fragments is usually much greater, partly because the radiants or fans of fissures may break the end pieces, partly because the fragments usually drop a greater or less distance and break over again. Under normal testing conditions, however, the pattern is remarkably uniform.

Siphon bottles usually have their origin very high, near the shoulder, particularly if they are machine-made. This is because the shoulder is the thinnest part of the barrel and the stress is highest here.

Occasional ginger ales and beers have a thin spot near the base, and sometimes the origin is here. In this case, only the upper fan of fractures is developed, and that rather poorly.

Wide bottles, like Steinies, sometimes break from an origin in the middle of the base, splitting the base in two. This may be partly due to annealing, partly to the severe bending stresses set up by internal pressure on a flat drumskin like a Steinie base. In most cases the origin, if on the side, will be near the blank mold seam, as this is the thinnest place. In bottles with severe bruises, the fracture may elect to begin at an obvious bruise instead of at a simple thin spot.

The fracture is propagated on the outside of the bottle, and incomplete fractures, not extending through the thickness, extend to the outer face and not to the inner. If the reverse is true, it is a suspicious sign, and probably implies that a blow was involved.

If the origin in the side is not vertical or nearly so, it is a suspicious circumstance; often it implies a blow, delivered at some other point.

If the origin is at a bruise, the question whether the bruise was made at the time of the explosion, or a long time previously, may be at stake. If it was simultaneous, the "cone of percussion" is usually developed and the origin is distinctly abnormal.

If the origin is horizontal instead of vertical, and if it is up on the neck or in some other unusual place, it usually implies a prying force exerted from outside or possibly a preëxisting fissure or "check." The margins of such a preëxisting check and the absence of the faint flutings at the very center of the origin are characteristic. The typical check is very shallow (*i.e.*, penetrates but a tiny distance into the thickness of the glass) and is many times as long as it is deep. Checks may have almost any orientation.

The complex cases resulting from prying on a bottle containing internal pressure, hitting such a bottle a blow, and so on, are among the most confusing. The internal pressure usually dominates the pattern after the start, and it is important to get all possible information about the start or origin.

The origin in a pressure break is well defined, and in 999 cases out of 1000, there is only one origin per bottle. In freak instances, two may be present. Whenever multiple origins are found, the circumstances are suspicious, for they are much more frequent in bottles that have been struck a blow so that the whole bottle is vibrating violently at the instant the fracture starts.

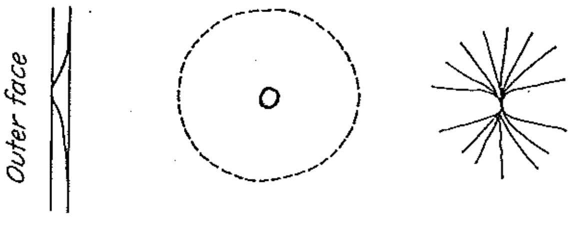

Fig. 5A Fig. 5B Fig. 5C

FIGS. 5(*A*, *B*, *C*).—A blow delivered on the outer face of a bottle may knock a conical hole through the glass. The cone may come out in one piece, with a broad internal base and a small apex on the outer face; Fig. 5*B* shows a possible ratio of the inner and outer traces. On the other hand, the blow, by deflecting the bottle wall inward, may produce tension on the inner face of the bottle of such an intensity that an origin is started there, which forks into a number of radiating or "star cracks" (Fig. 5*C*). Frequently, both the conical crack which starts at the outer face (Fig. 5*A*) and the radiating star cracks of Fig. 5*C* are formed concurrently.

There remain to be considered the features characteristic of externally applied forces, such as localized pressure from outside, a blow, prying off of the neck, and so on. Obviously, there is far greater variety in the details here than in the other cases. A blow can be delivered anywhere on a bottle; it can be gentle, moderate, or severe, made with steel, another bottle, or any other object, sharp, flat, or rounded. It may tend to crush the bottle bodily (which is not easy, however, with typical bottles) or to damage it locally.

Assuming that the bottle is empty, a blow from a round, hard object may drive a cone of percussion through it. If this can be found, it disposes of the case from a legal point of view. The cone is very small on the outside of the bottle and very large, relatively, on the inner side. Radiating fissures may start from the neighborhood of the cone and run on the inside face of the bottle (Fig. 5).

Forces which tend to crush the bottle without driving a cone through it may either start radiating cracks below the point of crushing (*i.e.*, on the inner face of the bottle) or they may start cracks on the outer face of the bottle at the places where the squeezing in one direction tends to produce bulging at others. At the bulging places, the outside of the glass is in tension; at the squeezed places, the inner side is in tension. Sometimes cracks start from both places, and being on opposite faces of the glass, such cracks can cross.

In general, any complex set of cracks can not be a thermal shock result unless the glass is terribly cordy or the thermal shock terrific. They must be either internal pressure or external force breaks. If the characteristic simplicity of the former is missing, the case is suspicious and must be examined carefully. Complex fractures can arise from bad annealing, but in this case the annealing must be so bad that the fragments still show a great deal of strain in a polariscope. If this is not the case, external force is indicated, but great patience and diligence is often required to interpret the fragments and pin down the exact cause and point of impact. The investigator must not guess in such cases but must be prepared to exercise almost oriental patience with the thing. The solution is sometimes found after the problem has been practically given up.

If the bottle is not empty, but contains carbonated beverage at the time of impact, the circumstances are still more complex, and the investigator must be prepared to take into account the fact that the initial cracks arise from impact, but their later course is determined by the internal pressure. He must also be prepared to allow for the effects of disannealing of either a commercial grade or palpable error. Some disannealing cracks are simple and rather resemble thermal shock cracks, but in this case they normally originate on the *inner* face of the bottle.

Part II was written to indicate that there are sound criteria by which the causes of fractures can be determined if enough of the bottle is left. Later, some of the fundamental sciences involved will be discussed.

III. Elastic Theory*

This chapter is likely to prove unpopular; in the first place it is not complete in itself but requires the reader to familiarize himself with the orthodox textbooks on the Theory of Elasticity or at least the "strength of materials," and in the second place, that theory is highly mathematical.

There is no use, however, in giving the orthodox theory here, because it has been done time and again by specialists. Further, there is no use in shirking the necessary study, and the investigator who wants to understand bottle breakage will have to face the discipline of the mathematical textbooks.

The present chapter, therefore, will concern itself chiefly with explaining which parts of the theory should be mastered in this particular case, and why; also with pointing out that the theory has its limitations and that the breakage of glass can not be fully understood in the light of the theory. This does not mean that the theory can be neglected; the student must master it. On the other hand, he must not assume that he can grasp all that there is to be known with the aid of the theory alone.

The Theory of Elasticity recognizes three varieties of stress in a material, *viz.*, tension, compression, and shear. The first two are grouped as "direct" stresses, and each may be regarded as the negative version of the other. They act "normally" or perpendicular to the stressed surface under consideration. Shear stresses act tangentially on the surface under consideration, and their relation to the direct stresses is somewhat complex.

A tensile stress is one that tends to lengthen a body; compression tends to shorten it. Shear stresses tend to make certain planes within the material (which were previously at right angles to each other) take up an inclined position. They are sometimes spoken of as "distortional stresses."

There is a great deal of confusion in the popular mind, and in the minds of geologists, who ought to know better, as to what is meant by "shear," but there is no ambiguity in the Theory of Elasticity. The student must master the concept as embodied in the latter and must not use it loosely. It has been pitifully misused by some of the best glass technologists, ceramists, and geologists, and marvelous structures of false theory, occupying hundreds and thousands of pages of valuable technical journals, have appeared to the everlasting confusion of science and industry. Until the student knows what he is talking about when he mentions "shear," he had better not proceed with his studies of breakage.

As a rule, the student will have no difficulty in understanding the nature of tensile and compressive stresses and in distinguishing strains from stresses, but he *will* have some difficulty in acquiring a facility in dealing with shearing stresses and in recognizing their implications—that they imply the existence of direct stresses in other directions.

A crack in glass is a response to a tensile stress and is never a response to any other kind of stress.[5] Glass can not be broken by compression or by shear unless there are tensions developed incidentally. This may sound strange because all the textbooks report a compressive strength for glass, *i.e.*, a stress which it will resist in compression and beyond which it will fail. All such reports are pure fiction and depend entirely on the details of the experiment. Glass will not fail under any compression that can be reached by human agency unless the faults of the apparatus used for testing produce incidental, and unintended, tensions.

In nearly all cases, the destructive tensions arise from rather intricate causes not suspected by the experimenter. None the less, they are there, and they can be disentangled by any observer with a working knowledge of the theory. It may be said categorically that a crack is always a response to tension, and the problem is to account for the tension.

In the same way, shear will not produce a crack. Shear may produce flow and will do so when the glass is hot, above the strain point (about 800°F), or hotter for typical commercial glasses; but flowing is not cracking. At room temperatures, commercial glasses are absolutely devoid of any ability to flow, but they all possess a marked ability to crack.

There is no immediate cause of breakage other than tension. Thus we say that we can break a bottle by a

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* November 18, 1936.

[5] P. W. Bridgeman believes that, under excessive hydrostatic pressures, he has succeeded in breaking glass in the absence of tension. An examination of his specimens and apparatus leaves us in doubt on this point. While keeping an open mind on the physics of high pressures, we can safely ignore such possibilities under the conditions of use of commercial glassware.

thermal shock, that is, by a sudden considerable change of temperature, and this no doubt appears to some men in the shops a thermal rather than a mechanical phenomenon. As a matter of fact, the glass breaks only because the change of temperature produces momentarily a high tensile stress in the walls of the bottle. The calculation of this stress is theoretically easy, but in practice it can only be approximated. In any case, because breakage depends not only on the intensity of the stress but also on its duration, any temporary or transient stress presents the investigator with a real problem, if he is trying to calculate whether breakage or not will occur. For that reason, a great deal of empirical experimentation is continually necessary where glassware is concerned.

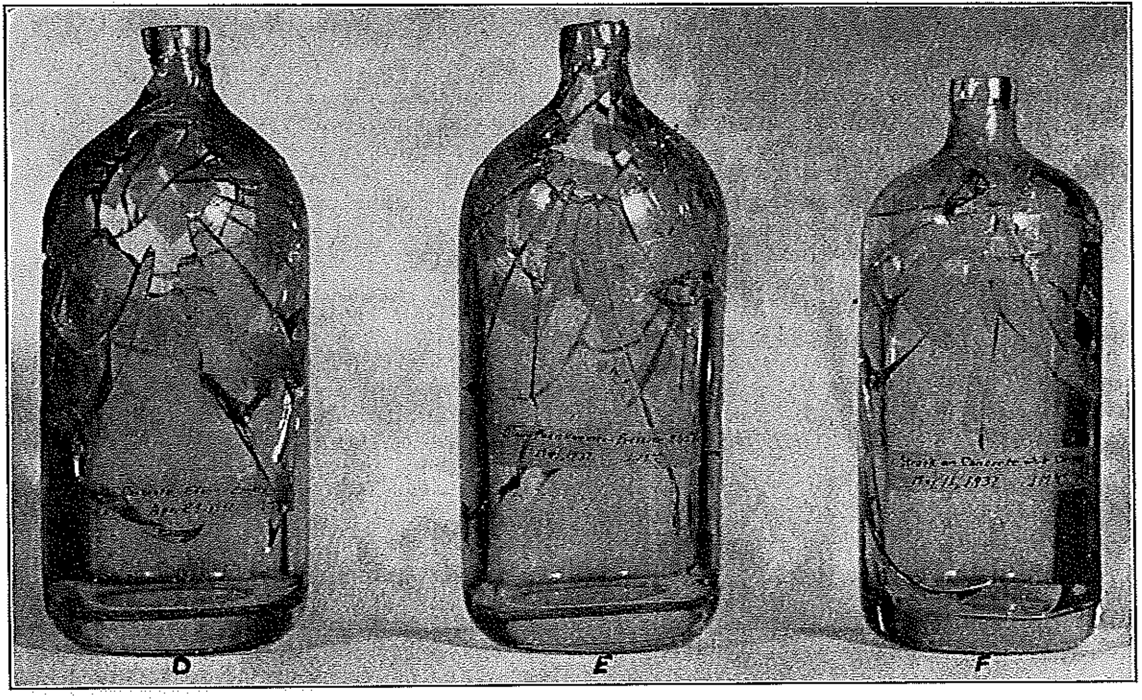

FIG. 5(*D*, *E*, *F*).—Siphon bottles broken by blows near their shoulders. Note that percussion cones have been driven through at the point of impact and that cracks radiate out from the origins like the spokes of a wheel.

The Theory of Elasticity is comparatively successful in calculating stresses as long as they are strictly elastic, that is, as long as they are reversible and can be made to disappear and the body to resume its original shape and size upon removing the causes of the stress. This may mean removing the external loads or internal water pressures or letting the body come to a uniform temperature. The theory is particularly adapted to handling cases where the stress is proportional to the strain; in steel, this is up to the "limit of proportionality"; in glass, it is up to the breaking point. The theory, on the other hand, is but ill adapted to prophesying what will happen beyond that point. The theory may be used to indicate that a danger point is being approached, but it can not describe the course of events during failure, nor can it reconstruct the tragedy afterward; for this purpose, and it is vital to our industry, we must know much else in addition to the Theory of Elasticity.

The student has to recognize that, in a single piece of glass, there may be tension in one direction and compression in a direction at right angles to it. In fact, seeing that any piece of glass is a three-dimensional article, there can be three "principal" or normal stresses at any point, each at right angles to the other two. In many of the cases that most concern us, however, the stresses can be effectively analyzed as two-dimensional. Thus a sheet of glass really has three dimensions, but in most of its parts one stress is virtually zero for most conditions of loading. This simplifies our work, but the student must be ever on the alert to recognize that we *have* introduced a simplification, and that the actual problem is *always* three-dimensional. As soon as a crack is produced, the third dimension has to be considered; this is discussed in Part IV.

It will probably not be easy for the investigator, in his early efforts to understand this subject, to grasp the connection between stresses or strains as shown in the polariscope and stresses or strains that produce breakage.

We have already stated that stresses do not produce breakage unless they are tensile stresses, and we have indicated that tensions, to produce breakage, must exceed a somewhat vague minimum value (which we shall discuss later) and must endure for a finite length of time. Cracks are a response to tensions of moderately high intensity and finite duration.

Polariscopic "strains," *i.e.*, color phenomena seen in the polariscope, are, briefly, indications of shear stresses. There can be high tensions and no color, if two principal stresses are equal and the shear stress is therefore zero.[6]

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[6] We are boiling it down (for brevity) to a two-dimensional problem.

There can be no tensions and high color, if we have high compressions without the two principal compressions being equal. The student must realize these limitations of the polariscope, which will be discussed more fully later.

For the present, it is important to point out that this does not mean that the polariscope can be neglected any more than the theory of elasticity can be neglected. The theory of polarized light is a subject in itself, and should be mastered; it is tedious but not inherently difficult. Note that as far as bottles are concerned, the features they have in common as containers—a general similarity of shape—and the features they have in common as products of somewhat standardized methods of manufacture make it possible to interpret polariscopic appearances empirically with some advantage. There is much room for error in interpreting the polariscopic appearance of anything so complex in shape and so hard to inspect fully as a bottle, but if it is known that a certain standard polariscopic appearance is associated with a bottle proved sound and good by other tests and by long experience, then it is comforting and reassuring to see that particular appearance regularly in the manufactured product.

In other words, the polariscope is useful to look for unusual appearances, and if they show up, suspicion should be aroused; but just what the unusual appearance may mean is often a complex matter to decide.

The subject of the connection between stresses and polarized light is called "photoelasticity." Polariscopic phenomena can be produced by other means, *e.g.*, by crystal structure or by the parallel orientation of ultramicroscopic crystals. The latter is occasionally observed in glass and is not a photoelastic matter at all. The observer must be prepared for it, but it is not likely to occur in bottle glasses of present-day (1936) composition. Whether it will occur in later ones remains to be seen.

We have already mentioned that the term "shear" is sometimes used in a confused and ill-defined sense, and we ought to point out that the term "elastic" is also used in a slovenly manner at various times. Thus we hear now and then of "elastic glass" as if it were a new invention, whereas all commercial glass is virtually perfectly elastic in the scientific sense. Unfortunately, there is some confusion even in scientific circles, and "highly elastic" may mean having a high value of Young's modulus, E, or may mean having an ability to recover perfectly the original shape and size on removal of stress. In the first respect, glass falls below steel, and it is comparable with bronze: E is about 10,000,000 lb./sq. in. In the second respect, it is equal to or better than steel. Pure silica glass (vitreous silica) is the most perfectly elastic substance known, in the second sense.

The terms "stress" and "strain" are often confused and interchanged. No great harm is done as a rule, but the student should not confuse or interchange them. Their meanings are absolutely distinct.

As will be shown in Part V, cracks usually originate at a surface, and the student as rapidly as possible should learn to visualize the limitations imposed on a complex stress system (the ellipsoid of stress) by the proximity of a free surface. The directions of principal stresses and of maximum shears are severely limited in the critical area, and this determines the initial form and direction of the crack.[7]

IV. Cracks Are Propagated*

Experiment No. 1

Take a sheet of thin window glass and heat one corner of it in a hot Bunsen flame. When the corner begins to glow red and the edges to soften and round off, withdraw the glass from the fire and hold it in the open air to cool. In a moment or two there will be a sharp click, and a fracture will appear on one edge of the glass near the boundary of the softened area (Fig. 6). After the click, the fracture will hesitate a moment and will then resume its course in hesitating, intermittent forward surges. Its progress will be slow enough to watch, and particularly in the later stages it may be slow enough to try one's patience, if one is inquisitive as to what direction it will take next.[8]

This experiment is a convincing introduction to the study of cracks, and after the investigator has once made it, he will never again fall into the common belief that cracks originate spontaneously throughout their whole extent. All fractures have a minute starting point and an ending point. They have a direction of travel and a finite velocity of propagation.

Fractures produced in this slow-traveling manner are highly polished and nearly featureless. They enter the edge of the glass at right angles thereto,[9] and do not normally make any exit.[10]

If thin window glass is used in the foregoing experiment and the heated area is extensive compared with the thickness of the glass, the stress system approximates to a two-dimensional one. After making a number of such experiments, the student should next take a piece of $^1/_4$-inch plate glass and heat a limited area near one corner. The stress system now begins to take on a three-dimensional aspect, and the fracture is no longer entirely described by its trace on one surface of the glass. It may have a curved contour as one goes through the thickness of the plate.

The experiment becomes increasingly difficult to perform with thicker glass, if one wishes to confine the heating near the corner. The glass bleeds the heat away too fast. The student should persist, however, and make a large number of such fractures in glass of increasing thickness, if available, and should observe particularly the details of the fractures. There is no other way known to the writer

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[7] Suggestions for reading in conjunction with this chapter are as follows:

(*a*) Any standard text on strength of materials.

(*b*) For advanced work, any standard text on Theory of Elasticity (*e.g.*, A. E. H. Love, Mathematical Theory of Elasticity, 4th ed. Cambridge, 1927.).

(*c*) F. W. Preston, "Glass as a Structural and Stress-Resisting Material," *Jour. Amer. Ceram. Soc.*, **16** [4] 163–86 (1933).

(*d*) F. W. Preston, "Use of Polariscopes in the Glass Industry," *ibid.*, **13** [9] 595–623 (1930).

* November 24, 1936.

[8] For a more extensive account, see Preston's "Study of Rupture of Glass," *Jour. Soc. Glass Tech.*, **10**, 234–69 (1926).

[9] The student should understand the bearing on this of the Theory of Elasticity chapter.

[10] The student should again observe the implication of the Theory of Elasticity.

in which the actual propagation of the fissure can be watched with so much completeness and satisfaction.

Experiment No. 2

Compare, if available, sheets of bottle glass (alkali around 16%), plate glass (alkali 13%), and borosilicate glass as to the ease of starting a crack and its velocity of travel. Note also whether a crack once started tends to stop more quickly in one glass than in the others. Make the same experiment with sheet lead-glass.

Observe whether the fissure-head is most advanced on the surface of the glass or in the interior; correlate this with what is known of the stress system.

Break out the partly detached area and examine the edge of the fracture in a bright light with the naked eye and with a pocket lens.

V. Fractures Begin at a Surface*

By a surface, we mean the boundary between glass and some other substance, usually the external air, but the "surface" may be an internal one. Thus, in the case of wire glass, many sorts of fractures originate at (and are caused by) the contact of the glass with the wire or the gas surrounding the wire. More rarely, very rarely in fact, a crack may be started from a large internal bubble, if the glass is strongly disannealed, so that a zone of severe tension surrounds the bubble. It is difficult, however, to start a crack in the interior of a solid glass mass in the absence of some "surface," such as the surface of a "stone" (clay or crystalline inclusion), a wire, or a pocket of some sort.

Dr. Littleton and the writer believe that they have occasionally succeeded in producing such a result, but as the specimen usually goes to powder when it does break under these conditions, the stresses being enormous and the strain energy released being far too great for the glass to absorb or "potentialize" by a simple break, we have never been able to prove the point to our complete satisfaction. From the student's point of view, if he is concerned less with academic possibilities than with the breakage of commercial glassware, it may be said categorically that all cracks begin at a "surface" or boundary of the glass.

This simplifies the problem of hunting for the origin, which, however, is not a difficult matter in any case, except with slow traveling cracks, such as are most easily produced by moderate temperature changes.

The appearance of a typical origin produced by internal pressure in a bottle was mentioned and figured in Part II, p. 3. The student should take three or four bottles, put them in the pressure-testing machine, and raise the internal pressure until the bottle breaks. Wrap the bottle in burlap or other cloth before the test so that it does not fall and break again; after it breaks, take out the pieces and find the origin. In a typical bottle, it will be in the barrel part; note also that it is on the outer face of the bottle, although theoretically, even if perfectly annealed, there would be slightly more tension on the inner face[11]; in commercially annealed bottles there is distinctly more tension there owing to the superposing of the annealing stresses. The crack begins, however, at the outer face in simple internal pressure breaks, because the outer face is much the weaker, structurally, of the two faces, and both faces are vastly weaker than the interior of the glass mass.

The external face is the weaker because it is blown against a mold in the process of manufacture, whereas the other face is blown against air. The metal of the mold produces a weakness in the glass wall, possibly due to microscopic "checks" or "chill-cracks," possibly due to more subtle causes, but in any case unequivocal. In the same way, when plate glass or wire glass is rolled on a casting table, the upper surface, touched only by a roller and that momentarily, is distinctly stronger than the under surface, which is chilled by the table and remains in contact with it for many seconds.

Dr. Littleton and the present writer have attempted to account for the fact that the surface is always weaker than the interior by an argument which undoubtedly has some truth in it,[12] but neither of us believes it represents the whole story.

This tendency of cracks to begin at a surface, independently of whether the surface has undergone scratching or bruising, eliminates one means (which would otherwise have been available) to discriminate between bottles that broke as a result of a manufacturing defect and those that broke as a result of subsequent misuse, because scratches and bruises are always on a surface. It becomes necessary for the student to recognize by less gross and more subtle signs whether there was in fact a bruise or a scratch preexisting at the site of the origin.

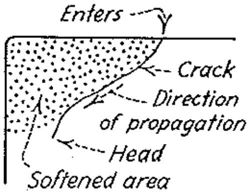

Fig. 6

Fig. 7

The typical origin developed under straightforward pressure is a plane mirrorlike area with a tiny puckered or crenelated place at the very origin. This crenelation is a short distance in from the edge or surface, or it seems to be best developed there. It is as if a pilot fracture were working in, trying to find the weakest direction, exploring the situation. It straightens out honestly at right angles to the gross maximum tension and produces the mirrorlike area, perfectly flat, and thereafter may become an oscillating discharge of energy, rippled, forked, or otherwise complicated. It may, on the other hand, become none of these things, but remain very smooth, as in some thermal shock cracks; the origin is then best located, if it can be located at all, by a little pucker, crenelation, or kink in the extensive mirrorlike area.

If, instead of this flat plane origin, the fracture shows a conical sort of fissure as the place of beginning, this is

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* November 26, 1936.

[11] Read up the Theory of Thick Cylinders in any treatise on elasticity or strength of materials.

[12] J. T. Littleton and F. W. Preston, "Theory of Strength of Thermally Toughened Glass," *Jour. Soc. Glass Tech.*, 13, 336–49 (1929).

strongly indicative of a percussion-cone flaw produced by a blow. The student should examine it closely, and if it looks like a blow, should consider how accessible the point in question is to a blow.

It will be shown later that, while percussion flaws are produced only by external force,[13] external force does not necessarily produce a percussion flaw. It is entirely possible for external pressure to produce an origin on the inner face of the bottle or to start a crack on the outer face with its origin quite remote from the point of application of the force. This is what de Fréminville[14] referred to as "rupture par contrecoup."

Experiments

(1) Bruise some bottles, preferably new ones taken from the leer, by bumping them on each other or by tapping with a hard steel hammer. Put little stickers on the glass pointing to the bruises. Test the bottles by internal pressure to destruction. Examine the points of origin and see if they coincide with the stickers. Note any peculiarities.

(2) Make a similar test with definite diamond or Carboloy scratches.

(3) Scratch a bottle horizontally on the neck and break the neck off by leverage. Observe the form of the origin. Repeat the experiment without scratching the glass, and observe how difficult it is to break the bottle.

Preëxisting checks sometimes exist in bottles and serve as origins of fractures. Such defective bottles are not always available; if they are, test one or two. Observe what happens to the expected puckers or crenelations.

(4) Break a dozen plate or window-glass laths in the cross-bending machines; observe where the origin is in each case, and account for it. Repeat the experiment, using $^1/_4$-inch rods in the rod-testing machine.

VI. Velocity of Propagation*

We have already seen that it is possible to make cracks which travel so slowly that it is tiresome to sit watching them—they may advance a fraction of an inch in many minutes (see Part IV, p. 7). On the other hand, a bottle breaking under internal pressure may be whole one instant, and less than $^1/_{500}$ of a second later it is fissured in all directions and ready to fall apart, as has been demonstrated by high-speed movie cameras taking several hundred frames a second; on one frame there is no sign of a crack, and on the next the primary fissure system is complete. The actual separation of the bottle into several pieces takes a few frames more, while the time taken by the fragments to fall after they are left unsupported in mid-air is much longer still. In the same way, the water, in the shape of a bottle, is left momentarily supported only by broken glass. It issues through the fissures and collapses slowly. On a high-speed film, the rapidity of the fissuring and the slowness of the falling down of bottle and water are in striking contrast. The one process is an almost inertia-free effect, the other is delayed by the sheer mass to be moved. Fissuring takes place under the tremendous forces of elastic stress; falling apart takes place under the relatively feeble action of gravity.

If the bottle were filled with gas instead of water at the time it broke, there would be an "explosion," which may be defined as the sudden expansion of a small volume of gas at high pressure to a large volume at lower pressure, accompanied by (in fact rendered possible by) bodily movement and usually rupture of the container walls. In our case, the bottle wall, in fragments, might be carried or flung by the expanding gas to great distances, and the movement of the fragments would be much more rapid than in a bottle broken under water pressure; but even under these conditions, the propagation of the fissures is a vastly more rapid action than the flight of the projectiles.

Until recently, we had few accurate data on the velocity of propagation of high-speed cracks. Schardin, in Germany, has lately succeeded in photographing cracks made by a bullet and in comparing them with the velocity of bullets and of sound in water.[15] He concludes that in ordinary glasses cracks travel at constant velocity, about one mile a second, twice as fast as a fast rifle bullet, or else stand perfectly still. Edgerton at M.I.T. has also succeeded in making excellent pictures of high-speed cracks, and more work is in prospect.

If we took a very long rod of glass (Fig. 7)[16] and tried suddenly to stretch one end over a short distance, the stretch would not instantly affect the whole length of the rod but would be confined to a zone or length near the end in question.

This end would be overstressed because all the stretching would be concentrated in it, and, in an attempt to distribute the stretching uniformly along the rod, this piece would give a "yank" to the part immediately to the left of it, which in turn would repeat the process, like the jar that travels down a freight train from car to car when the locomotive starts. This "pulse" or "jar" traveling down the rod is an "elastic vibration," and it travels with the speed of sound in glass. We have already seen that this speed is of the order of 15,000 ft. per sec.

Because the first end was overstressed through the concentration of all the "stretch" in a limited length, the pulse that travels down is overstressed and does not produce a uniformly distributed stretch by the time it reaches the far end. Like the freight train which "chatters" and complains of the pulse for a second or two after the first "yank" goes by, the rod transmits the whiplike action of the pulse to the far end, where it is reflected and travels back again, and the process continues for a while until the action is dissipated by internal friction or outside braking influences.

Now let us suppose that the rod has been stretched uniformly and suddenly a crack is started in the middle of its length; the tension in the immediate neighborhood of the fissure is suddenly relieved, and the zones immediately on either side of it are suddenly restored to unstretched

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[13] The term "external force" might perhaps be better rendered "extraneous force." The force does not have to be external to the whole bottle. Place a steel bicycle ball or a nickel coin inside a milk bottle and give the bottle a sharp tap against the thigh; a percussion cone can be driven through the glass wall from the inside face.

[14] Read de Fréminville's article, "Recherches sur la Fragilité," *Rev. de Metallurgie*, No. 9 [Sept.], pp. 971–1056 (1914).

* December 7, 1936.

[15] H. Schardin and W. Struth, "High Frequency Cinematographic Investigation of Breaking Process in Glass," *Glastech. Ber.*, **16**, 219–27 (1938); *Ceram. Abs.*, **18** [1] 17 (1939).

[16] See Part IV, p. 7.

length. This pulse of stress-release likewise travels with the velocity of sound (or would do so), if the fissure could be produced completely across the rod in zero time.

In practice, the propagation of the fissure and the release of stress, or perhaps we should say, its redistribution, proceed concurrently. As the fissure advances, the stress, which previously existed across the prospective fracture-plane, is released, and the overstressed zone is concentrated at the head, or periphery[17] of the advancing fissure.

It would appear then that, because stresses can not be redistributed at a speed greater than the speed of sound in glass, cracks can not be propagated with any greater speed. On the other hand, we know that they can be propagated with great slowness, and it would seem that any speed from zero to 15,000 ft. per sec. is possible.

The final appearance of the fracture-surface tends to be quite different with slow-moving and fast-moving fractures. Slow-moving fractures are highly polished, because the stress is redistributed very slowly, and no measurable pulse or vibration is transmitted through the glass while the fissure advances.

If the crack is advancing rapidly, the redistribution of stress is rapid, and in a particular zone, near the head of the fissure, a lot of strain energy is "released" or canceled in a fraction of a second. This necessarily starts a sizable pulse of energy traveling out into the body of the glass. Because, in practice, there are always boundaries to the glass within a tiny fraction of one second's travel from the fissure, the pulse or wave is reflected, usually at more places than one, and a complicated set of "standing waves" is set up.

It follows that the stress at any point is not constant in amount but is "periodic," fluctuating with time through higher and lower values. The fissure therefore tends to advance in jerks. Further, because the reflections are not simple in direction or number, the stress does not fluctuate simply in amount but also in direction. If the fluctuations of both kinds are small, the fissure will show a faintly rippled surface. These ripples are of great diagnostic value, as they tend to be somewhat uniformly concave toward the origin and serve to locate it.

If the fissure is traveling very rapidly, the fluctuation of stresses becomes very great. At the head of the fissure, in particular, where the stresses must in any case be high in order that it shall travel rapidly, there is an instability produced through fluctuation in the direction of the stresses. A fissure, being a response to pure tension, must advance exactly at right angles to the tension, but if the tension at the fissure head is fluctuating rapidly in orientation, it is certain the plane of the fissure as a whole can not be reoriented to this extent. The attempt to make this reorientation splits the fissure into thousands of small elements, each of which has sufficient mobility for this purpose. The elements may be, in the first instance, ultramicroscopic, but as soon as they reach microscopic size, they announce themselves to the naked eye as a dulling of the bright polished surface, producing a mat or gray appearance, which in earlier papers the writer called "hackle texture," though that is not the best description. Under the microscope, it is seen that a vast number of tiny "Woodworth feathers," or "de Fréminville stries" are present. In their grosser manifestation, these have found their way into the law courts of New York State as "Rogers' striations," and have been confused with the "striae" or "cords" of optical glass, and other kinds of glass, which are actual heterogeneities in the glass substance. It scarcely needs saying here that the "feathers" or "striations," whether macroscopic, microscopic, or ultramicroscopic, have nothing to do with "cords" or with any heterogeneity in the glass. They are simply a consequence of fracture under vibratory stresses and are present in the most homogeneous of materials.

In practice, a fracture may never develop to the point of having a mat surface, but in many kinds of violent fractures, a zone of gray borders the brightly polished area which includes the origin. If it does, it is generally followed by macroscopic "striations" and by forking of the fracture into several fissures. The forking is accomplished as a development of the "striations," a "striation" being a split in the fissure-front which may become an entirely independent crack, branching off from the parent one.

It must be emphasized that a striation is primarily, in fact solely, a response to an attempt of a fissure to advance while the stresses at its head are not strictly at right angles to the plane of parting so far constructed. It is not essential that the stresses should be vibratory. As a crack advances, it may reach a region where the stresses are no longer perpendicular to its plane. In such a case, striations, frequently very large ones, may develop, but there will probably be no noticeable gray area. The gray area is composed of thousands of minute "striations" that got started by a change in stress-direction and then were killed by a reversal thereof. Thousands more were produced on the other swing of the pendulum and were killed in their turn.

Seeing that many of these striations are less than $^1/_{1000}$ inch in length and that the fissure as a whole may have been traveling at a speed comparable with the speed of sound, it seems likely that many of these hackle-texture striations may have been made complete in a fraction of a millionth part of a second.

Large striations are seen characteristically on the last-made parts of fissures. Toward the end of a fissure's travel, it will frequently be advancing on a broad front into a region where the stress is of moderate intensity and incompatible in direction. The fissure tries to turn over on its side, warping its plane as it were, and develops a number of splits which later form striations.

The student, therefore, must master the significance of ripple marks and of striations and understand what they imply and what they do not imply. There is no great difficulty, once the ability to visualize things in three dimensions has been acquired. The nature of a striation can not be properly indicated in a drawing, which has only two dimensions, and while photographs can be taken of "dead" striations, they give no clue as to their real character while in process of formation.

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[17] We may speak of the "head" of the fissure, if we think of it as advancing in one dimension, but of the "periphery," if we think of it, as it always is, *viz.*, a two-dimensional area-of-parting advancing into a three-dimensional mass of glass. Initially, fissures tend to be semicircular areas, and the crack advances at all parts of its perimeter.

The form and features of dead striations have been well described by de Fréminville, particularly as applied to bitumen. The student should read his articles and should repeat some of his experiments with bitumen (asphalt) or pitch, preferably in cold weather.[18]

The nature of striations and their method of production while "alive" have been described by the present writer[19]; the student should read this paper.

Striations in course of formation can be most easily studied by tearing apart jellies (Reid-Moir, Littleton), and if the student makes the experiment he will see that vibratory stresses are not necessary to their production, but only "warped" stresses. Stresses vibratory in orientation necessarily tend to produce striations, but they are not essential to that end.

It should be observed, however, that the presence of striations in a substance as strong as glass normally implies some "snap" or violence on the propagation of the fissure, for if the fissure is traveling under a minimum of urging and comes into a region where the stress is not correctly oriented, it will find the effort to proceed too great, and instead of splitting its front and forming striations, it will simply stop, and that will be the end of it. Thus while striations do not theoretically demand a vibratory stress system, in practice they imply a certain amount of violence.

The student, of course, must understand that the presence of striations does not imply *external* violence. A bottle breaking suddenly from total disannealing will show gray surface and striations just as much as one that has been struck by a hammer. To determine what broke the bottle, we need not only to study the individual fracture surfaces, but their arrangement into a pattern of cracks, and particularly the appearance of things near the origin, if possible.

NOTE: It is quite conceivable that our knowledge of the actual velocity of propagation will undergo radical changes in the near future, owing to Schardin's work and that of other experimenters. Some of the statements in Part VI, which appeared reasonable in their wording in 1936, now appear dubious, and in a year or two it may be necessary to rewrite this chapter.

VII. Forking of Cracks*

It is a well-recognized fact that when a piece of glass is broken, by falling or by being struck, it breaks into rather a lot of pieces. This is different from what we observe with most other materials. Thus, when we break a stick to put on the fire, there is no difficulty in breaking it into two pieces. A bar of cast iron or mild steel, broken in tension or cross bending, will likewise normally break into two pieces. A mason usually has no difficulty in breaking a brick or stone into two pieces, but this experiment is misleading, for the mason normally marks his work with a groove or scratch and skilfully guides the crack. In the same way, a sheet of glass can be broken into two pieces if it is first scratched with a diamond or glazier's wheel to guide the crack, while a brick of good manufacture, if struck a violent and unskilful blow, will usually be found in more pieces than two.

None the less, the property of glass which results in its typically falling into a number of fragments is important, and while the fact itself is everywhere recognized, few people have paid the slightest attention to the mechanism by which it is brought about. It is possible to break a piece of glass into two pieces by one action and then to break each piece into two more by a subsequent action, but this is not the normal means by which a glass bottle or window is reduced to fragments. The crack usually starts at a single place, but it divides by *forking*.

Forking, as shown in Part VI, is made possible in its typical form by a splitting of the wave- or fissure-front. A fissure may be split by intersecting a bubble or similar inclusion in the glass, and when the two halves of the fissure have circumnavigated the bubble, they rarely match up exactly; one is displaced a trifle with respect to the other. Thus even if they align themselves a moment later, there is almost invariably a little "tail" or marking on the fissure for a short distance. Normally, however, the splitting of the fissure front does not necessitate any visible cause, such as a bubble, but can be accomplished simply by a change of stress orientation.

It is conceivable that while no visible bubble or discontinuity is present, the possibility of splitting the fissure first, thus starting a "striation" or "hackle," depends on the presence of ultramicroscopic discontinuities. Whether these discontinuities represent the ultimate molecular structure of the glass or whether they represent the "flaws" of Griffiths, Smekal, and others is not yet certain.

The simplest form of forking is when a fracture divides into two fissures of equal importance. This apparently occurs frequently and may indeed be the most usual procedure, but since each fissure thus produced may immediately split again, it is common to see what appears to be a sheaf of fissures radiating from a single point. The author has called such points "radiants" and has also referred to the bundle of fissures as a "radiant," because there appears to be no special significance attached to the point alone.

Experiment

Take a lath of plate or window glass, 1/4 by 2 by 18 inches, and break it by cross-bending in the cross-bending machine or any experimental rig. Unless the glass is very weak, it will not break into two pieces by a simple transverse fracture. On the contrary, if the origin is in the middle of the width of the lath, the fracture will fork just beyond the mirrorlike zone and will reach each edge of the lath as a bundle of cracks distributed over a fan-shaped area with an included angle of about 45°. If the origin is near or at one edge, the fan-shaped bundle of cracks will extend toward the other edge.

Cross bending therefore tends to produce two large pieces of glass and two (sometimes only one) groups of dagger-shaped small fragments.

Experiment

Take a 40- or 60-watt electric lamp bulb, before the electric works are put inside, and subject it to internal pressure on the special testing machine for the purpose. Be careful not to have too much travel on the plunger so

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[18] Or, of course, the specimens may be placed in a refrigerator for a while.

[19] See footnote 2, p. 2.

* December 8, 1936.

that there is no great "follow-through" when the bulb breaks.

Observe that the spherical part of the bulb is covered with radiating cracks, which usually arise by the repeated forking, into two cracks, of a single crack. This repeated bifurcating makes it somewhat difficult to refer to a point as a radiant, but the whole structure is obviously akin to the radiants we are already familiar with.[20]

Experiment

Take a circular disk of plate or window glass, 4 or 5 inches in diameter. Set it centrally over a 2- or 3-inch hole in a $^1/_8$-inch iron plate. Put the plate on a tripod and set a lighted Bunsen burner under the hole to heat the central part of the glass disk while maintaining the outer parts thereof fairly cool. After some minutes, the disk will fly to pieces. It is well to build a fence of some sort round the disk on top of the iron plate to prevent the bits from jumping all over the laboratory.

The origin will usually be not central but near the junction of the heated and cool parts of the glass. Why?

If the hole is not much smaller than the glass disk, the origin may be at the edge of the disk. Again, why?

If the origin is not too far from the center, the radiant will extend over an angle of 180° instead of 45°. Once more, why?

The student ought by this time to be able to answer these questions.

Experiment

If the weather is freezing fill a number of bottles with water, and, without capping them, put them on a shelf out of doors overnight. The water will turn partly to ice, and the first ice formed will plug the neck of the bottle tight (remember that ice floats if free to do so). After the neck is plugged, further crystallization of ice on the bottle walls will develop great hydrostatic pressure, because ice is more voluminous than water. The bottle will break, but the ice, like a manikin inside the bottle, will support the pieces in place.

This is one of the best ways to study the fractures in bottles subjected to internal pressure and is available to everyone without apparatus, if they live in a cold climate part of the year.

Observe that if the origin is in the barrel part of the bottle (the barrel being a simple plain cylinder) the angle of forking is about 90°.

If a number of bottles are available, it will be found that some are much more forked and fissured than others. Those with the most forks broke at the highest stresses, *i.e.*, were the strongest bottles.

This law is general. Try it on cross bending of laths; measure the load at breakage and compare the extent of forking on a number of specimens.

VIII. Annealing and Its Influence on Breakage*

In the law courts, as a result of confused testimony given in the Smith *vs.* Peerless case, there has arisen a confusion not only between Woodworth's feathers ("striations") and internal heterogeneities ("striae" or "cords"), but also between striae and disannealing, because both tend to produce optical effects in the polariscope. There is little resemblance between the three phenomena, and only the most superficial knowledge could have confused them. In the present chapter, we are concerned only with annealing and disannealing of homogeneous glass.

The process of annealing, expressed in its crudest terms, consists in cooling the glass slowly from about 900°F to room temperature, so that at any instant all parts of the article are at nearly the same temperature. Ware of this sort shows but slight optical effects in the polariscope. "Disannealing" consists in cooling the glass rapidly, particularly in the range 900° to 700°F, so that pronounced differences of temperature exist at any instant between one part of the bottle and another. Such ware normally shows brilliant colors in the polariscope. Obviously, however, annealing and disannealing are matters of degree.

In the manufacture of optical glass for telescope lenses, microscopes, spectroscopes, and so forth, a high degree of annealing is necessary; otherwise, the final optical image in the scientific instrument may show astigmatism, coma, and other evidences of imperfect correction. Further, the refractive index of the glass as a whole may be distinctly in error, producing errors in the focal length of the lenses as well as distorted images.

In glass bottles, we are not bothered with these problems, and the kind of glass we want is not that which is most perfectly annealed in the optical sense, for such glass is "dead-soft," easily scratched, often easily broken, and, in general, not so strong chemically as glass that shows some optical effect in the polariscope. Glass can be strengthened by moderate disannealing; in fact, a whole industry exists in the strengthening of glass by this means. Under favorable conditions, high disannealing produces excellent results. Thus Corning's oven-top baking ware is deliberately highly strained by disannealing; this is also true of Corning gage glass covers, which protect operators from injury when a boiler-gage glass bursts. Again in Europe, a great deal of hardened glass, Securit and the like, is used for automobile windshields, and the windows on the promenade deck of the *Normandie* and the mirrors at the head of the main stairway are made of this deliberately disannealed glass.

It must not be supposed, however, that bottles can be allowed to cool uncontrolled with great rapidity and be safe. The shape of a bottle is not favorable to this treatment, and moderation must be exercised.

Experiment

Take a few bottles as they come from the forming machine at a glass plant, red hot, and stand them on an asbestos pad in a place clear of draft to cool rapidly. Possibly some may break by the time they are cool. If they all break, it will be necessary to put up some screening around them, but a minimum should be used, consistent with getting whole bottles when cold. These bottles must not be picked up thereafter except by the neck, very close to the "finish"; use gloves, and do not put your face too close. The bottles occasionally break apart spontaneously at unexpected times.

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[20] *Cf.* J. M. McCormick, "Tests of Strength of Electric-Lamp Bulbs with Special Reference to the Time Factor," *Bull. Amer. Ceram. Soc.*, 15 [8] 268–71 (1936).

* December 9, 1936.

Inspect the bottles (when thoroughly adjusted to room temperature) in the polariscope and observe the brilliant colors. Hammer one bottle on the other, barrel on barrel. It will be found impossible by the use of any ordinary amount of force to break such bottles.

Scratch the outside of the base of the bottle by rubbing it on another bottle; the bottle may fly to pieces because the outside of the base is frequently in tension and needs only a scratch to start a crack.

Drop a piece of broken glass the size of a barleycorn or a little larger into the inside of the bottle. If the bottle does not instantly break, swirl the broken piece around inside; by and by a scratch will be made, and the bottle will break into many pieces. The neck is always left intact, the barrel is rather broken up, and the base is more or less shattered.

Reconstruct the broken bottle with sticking paper. Observe that the cracks are quite different in pattern from those produced by a typical internal pressure break.

Experiment

Give a few bottles, thus disannealed, a severe thermal shock test. It will be found that they are exceedingly resistant to damage by sudden quenching.

The reason is obvious as far as the bottle walls are concerned, for they are in strong compression as a result of disannealing; but a normal thermal shock break begins in the base, and it is not obvious that the base should be strengthened by disannealing. In fact, the experiment of scratching the outside of the base suggests that it has been made more vulnerable. (There is here a matter for further research.)

Experiment

Give a few such bottles an internal pressure test; they will usually be found to be abnormally strong.

When a bottle has been broken by internal pressure combined with disannealing, reconstruct the bottle and examine the pattern of cracks. (Many breaks that have been attributed to disannealing are really due to internal scratching.)

Bottles totally disannealed, *i.e.*, that never went through a leer or oven, but were cooled in the open, are rarely encountered in practice. What is found are bottles that went through a leer in which the régime of temperatures was a long way off normal. Such bottles may have a grade of annealing corresponding to a temper greater than temper 6 (Glass Container Assn. Standard Grading of Annealing Disks) and may break spontaneously at unexpected times, often after giving long service. They may, on the other hand, break in pasteurizing or merely in sitting around at the customer's ware house. The most usual break is a simple crack taking out the base of the bottle somewhat after the fashion of a thermal shock break, but with the origin most likely on the inner face of the bottle, close to the junction of base and side walls.

The parts of bottles which break from disannealing strains will usually still show strain after breakage, though the intensity and distribution have been somewhat changed by the act of breaking.

Experiment

Obtain from a manufacturing plant a supply of bottles which went through the leer after a lengthy shut-down of the forming machine; for a time, such bottles are apt to be overstrained. Experiment on the strength of such bottles under various conditions and see whether they can be provoked to spontaneous failure.

The general subject of annealing in all its ramifications can not be dealt with here. The physical processes involved in annealing include not merely the obviating of residual stresses of dangerous magnitude when the glass is cold, but the "stabilization" of the glass at a "constitution" (or atomic arrangement) somewhat different from that of disannealed glass. This "constitution," frozen into the glass in the last stage of annealing, is an arrangement of atoms which is approximately the stable arrangement at a temperature of about 700°F, while that constitution which is "frozen in" by quick cooling may correspond roughly to the arrangement stable at 800° or 900°F. In general, in chilled glass, the density is less, the refractive index less, and the electrical resistance much less, than in slowly annealed glass.

The laws governing the rate of release of stress, in terms of the stress present at any instant and the temperature at that moment, are quite complex and have been the subject of much experimentation and theorizing.[21] For the present, we are concerned mainly with the problem of how annealing affects the strength of bottles and how it modifies the fracture system.

IX. Crushing Strength and Impact Strength*

Glass, as such, is almost infinitely strong in pure compression, and no one has yet succeeded in measuring the collapsing strength of glass under such conditions.[22] None the less, the textbooks are full of quoted values of the compressive strength of glass, and what is quoted is the crushing load per unit area observed in a particular experimental setup of a highly imperfect character. The limitations of our materials, available for constructing testing machines, prevent us from carrying out the test we think we are carrying out, and we break the glass by unintentional tensions.

Leaving this matter aside, it remains true that bottles can be crushed and broken by superficially compressive actions. Thus a bottle may be broken in the capping machine (which puts the caps on the bottles after they are filled with carbonated beverage). This machine exerts a sudden downward thrust as it closes the cap on the "finish," and sometimes the bottle collapses. This is usually due to the bottle being out of plumb, "drunk," or to its being tilted by something lodged under the base, or to imperfect adjustment of the capping machine. Mere compression will not do the trick.

In practice, bottles bump each other somewhat frequently when out in the trade. It is usually easy to break the neck off one bottle by hitting it with another, and the barrels of the bottles are easily bruised, if not broken, but

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[21] See G. W. Morey, Properties of Glass, Chapter VI. Reinhold Publishing Co., New York, 1938.

* December 9, 1936.

[22] Dr. Littleton informs the writer that, under high hydrostatic pressures, water can be forced into the "pores" of glass and can disintegrate it. The same pressures, applied to certain other liquids, do not cause penetration, and the glass survives unharmed. Bridgeman failed to break it under the highest hydrostatic pressures yet attainable in any laboratory.

this depends largely on the condition of the inside of the bottle, whether bruised or not.

With the present tendency toward thin-walled bottles, it may become increasingly important to determine that the bottles will stand not merely hydrostatic internal pressure but localized external pressure or impact.

Impact testing has been used to some extent in England and to a less extent in this country, particularly for milk bottles; it usually consists in striking the glass article a blow with a pendulum hammer, the hammer having a known weight and moment of inertia and the arc of swing being regulated. The test is made both on the barrel of a bottle and on its "finish," separate hammers of different weights being used for the two tests.

Whereas an internal pressure test is fairly readily defined, subject only to minor possibilities of variation, impacts present an unlimited number of possibilities. The blow may be delivered at a great variety of places on the bottle; the bottle may be held or supported in a variety of ways; the metal or material of the hammer may be varied, and the nose thereof may be pointed, flat, or rounded to all sorts of radii. In practice, a bottle may meet with all sorts of impacts from all sorts of objects, and there is no possibility of testing it against all of them. We can afford only a limited amount of testing, and the impact test has not yet met with general approval.

The pendulum test is no doubt derived from the steel industry: there, a notched bar test is made by striking the bar with a heavy pendulum and measuring the reduction of pendulum swing. This is known as the Izod or charging test. After a good deal of experimenting with pendulums of various sorts, we have abandoned them in favor of a "dropping ball" test.

This consists in dropping hardened steel balls from a known height upon various parts of a glass bottle. It is remarkable what a severe impact seemingly frail bottles will stand, provided the inside of the bottle is not scratched. If the inside is scratched and the impact takes place on the outer face close to it, the bottle is apt to be found very weak. The impact test in fact is one of the best tests for the existence of internal defects.

The student should try impact testing with the dropping ball, using both the simple form and the repeating electromagnetic test. It will be found that bottles are far from simple in their responses to impact and that rigidity is usually an undesirable feature when the impacting object is hard.

Another test that has been used is to drop the bottle itself upon a hard anvil, which may be concrete, cast iron, or other material.

In the flat glass industry, impact testing has, in the last few years, become an important matter as a means of determining the merits of various forms of safety glass. Such glass may be hardened (Securit or Armorplate) glass, or laminated (Triplex) glass. Whereas a $^3/_4$-inch steel ball is convenient for bottle testing, much heavier balls are used for safety glass testing, and, in addition, heavy bags of lead shot and conical-pointed steel darts are used. The various forms of safety glass react differently.

The static crushing strength even of thin-walled bottles is normally high, so that tests call for a powerful machine and are probably a little irrelevant. With internally damaged bottles, it is possible that some information of value might be obtained. To crush a bottle normally requires a heavy localized load.

Combined impact and internal pressure is a common cause of bottles breaking in practice. The disentangling of two simultaneous factors is often difficult, and while the student at this stage may well make a number of tests of this character, using proper precautions, we shall not discuss the subject at length. It will often be found that such fractures, in their later stages, are scarcely distinguishable from ordinary pressure breaks, but near the origin they are entirely different.

X. Numerical Data on Strength*

Thus far we have considered the causes that produce fracture, *viz.*, the manner in which the fracture originates and spreads, the pattern formed by the crack or cracks, the appearance of the fracture-surface, and much else of a qualitative character. It will be obvious, however, that we need quantitative data on the pressures and temperature differentials that bottles will stand. On this subject, as well as on the strength of glass rods, laths, bars, and plates, a great deal of empirical information has been acquired by many experimenters.

Until recently, most investigators have not recognized that the rate of loading or the duration of the test exercises a profound influence on the values of the strength obtained, though this matter has been known after a fashion for a generation past. (The subject is discussed in Part XI, p. 17.)

It has been recognized that there is a great deal of variation in strength from specimen to specimen, even when the simplest form of specimen is used, the specimens are as nearly identical as possible, and the rate of loading is accurately controlled. Table I gives the breaking stress on a number of glass laths, all alike as far as the eye could tell or their past history disclosed, when tested under the most uniform conditions available.

TABLE I

POLISHED PLATE GLASS GROUND EDGES

($1^1/_2$ by $^3/_{16}$ by 10 inches)

Continuous loading (10,000 lb./sq. in./min. loading; 8-in. span)		Continuous loading (10,000 lb./sq. in./min. loading; 8-in. span)	
Specimen No.	Breaking stress	Specimen No	Breaking stress
1	8880	12	9340
2	8380	13	10460
3	10120	14	8630
4	9830	15	10640
5	10160	16	7450
6	9450	17	8650
7	10160	18	9040
8	9770	19	9830
9	11120	20	7890
10	10200	21	8720
11	6500		
		Av.	9295

Again, fifty beer bottles, taken from the same leer and the same forming machine over a brief period, yielded results, given in Table II, when tested by the most accurate

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* December 15, 1936.

machine available (Glass Container Assn. Standard Pressure Test).

TABLE II

DISTRIBUTION OF BREAKING LOADS

One-Minute Sustained Progressive Hydrostatic Pressure Test

(50 amber beer Steinies)

Breaking load (lb./sq. in.)	No. broken	Total broken	% broken
175	0	0	0
200	3	3	6
225	7	10	20
250	12	22	44
275	10	32	64
300	9	41	82
325	4	45	90
350	4	49	98
375	1	50	100

Average strength 260 lb./sq. in.
(12 lb./sq. in. subtracted for loading interval)

Obviously, in the form quoted, there is no means of telling whether the glass in the laths or the glass in the bottles was the better material because in the one case the breaking stress is reported, whereas in the other case only the breaking load. What we should like is some means of reducing the figures to a common physical property of the glass, *viz.*, the tensile strength.

In the case of the laths, the calculation of the breaking stress (modulus of rupture) from the breaking load was easy. The lath is of substantially uniform cross-section, and the method of loading is precise. The maximum tensile stress developed in the lath is easily calculated and is reported as the "modulus of rupture," being deduced from the theory of the bending of beams. It is, in fact, so much easier to test glass by bending than by a direct pull that most of the data on the tensile strength of glass have been acquired by the indirect method.

In the case of bottles, the calculation is theoretically not difficult, provided that the bottle is cylindrical and that the break starts in the cylindrical part. The theory of the strength of thin-walled cylinders subjected to internal hydrostatic pressure is simple, and the theory of relatively thick-walled ones is not very complex. But in practice, serious complications are apt to arise because a bottle of nominally circular contour is nearly always more or less elliptical even on the outside, and the inside is usually noticeably so. Under internal pressure, the interior tends to become more circular, and this introduces bending stresses which may easily exceed the stresses derived from the theory of cylinders.

Still further complications arise from the fact that the cylindrical part of most bottles is not very long, and the reinforcing effect of the bottom and the top may not be negligible. Yet again, in commercial bottles, the annealing is not optically perfect, and a certain reinforcement of strength is produced by the disannealing. Finally, the theory is not applicable in any case where the fracture begins in the base or up on the shoulder.

As if these complications were not enough, we discover that the tensile strength of a glass object tends to vary greatly with its size. Thus a glass fiber gives a much greater strength than a thin rod, and a thin rod is much stronger than a thick one, so that if we are successful in calculating the strength of the glass in the bottle by an experiment on the bottle, we do not know how big the rod is with which we should compare it. In fact, in practice, the only thing we can do is to melt the bottle down and draw a rod from the melt to compare with the other glass in the other rods.

We have already discussed (Part V, p. 8) the fact that fracture originates at a surface and that the inner face of a bottle in its pristine condition is much stronger than the outer face. Thus, according to the theory of the strength of hollow cylinders, particularly thick-walled ones, the inner face is more highly stressed by internal pressure than is the outer one; yet in practice the crack begins on the outer face.

If the student now understands that there is a great deal that is arbitrary about any attempt to measure tensile strength, he will understand that the quoted values, in the textbooks, are subject to severe restrictions in interpretations.

With very fine glass fibers, $^1/_{10,000}$ inch in diameter, strengths up to one million pounds per square inch and higher are observed, and there is every reason to believe, on theoretical grounds, that glass in general should be as strong as this; in practice, however, we do not find bottles or rods indicating such a strength.

As tested in the laboratory, rods or laths frequently show a strength of the order of 10,000 lb./sq. in. With small rods in good condition, 20,000 lb./sq. in. is often met; with laths 2 in. wide and $^1/_4$ in. thick, the value is apt to be less than 10,000 lb./sq. in. Rough-rolled glass will frequently give figures around 7000 lb./sq. in., but the two sides of the glass are not equally strong, and the weaker side may be around 5000 lb./sq. in. Large sheets or panels of rough-rolled glass may be down to 4000 lb./sq. in. or a little less.

The strength of bottle glass, as indicated by the thermal shock test, is usually of the order of 3500 to 4000 lb./sq. in., but it might be less if the bottles were perfectly annealed. The strength, as calculated from the internal pressure they will stand, is usually of the same order of magnitude.

Bottles taken from the leer and handled without touching each other are twice as strong as bottles that are rubbed gently on each other when still warm and clear. Bottles rubbed gently sidewise on each other are weakened more than those that are bumped together somewhat roughly in this clear condition. This is presumably associated with the fact that bumping produces mainly compressive stresses, while tangential drag produces more tension and therefore deeper cracks behind the point of application.

Experiment

If possible, the investigator should check the last point for himself with bottles in their pristine condition and in normally inspected condition. They may be preserved in the former state by smearing with cold cream at the leer end before they can touch each other.

As far as bottles are concerned, we do not usually attempt to express their strength in terms of tensile stress, but simply record, in the case of internal pressure, that pressure at which the bottles, on the average, break.

In the case of thermal shock, we usually give the temperature differential that breaks 50% of them when the quenching medium is water. As will appear later, there are several factors that must be specified before these figures mean very much.

A thick-walled soda bottle, when new, may have a strength in excess of 1000 lb./sq. in. hydrostatic pressure. A typical siphon bottle may average 500 lb./sq. in. on a "snap" test. A typical beer bottle may run around 400 lb./sq. in.; a lightweight Steinie may be around 300 lb./sq. in.; and a square bottle may be only 50 lb./sq. in.

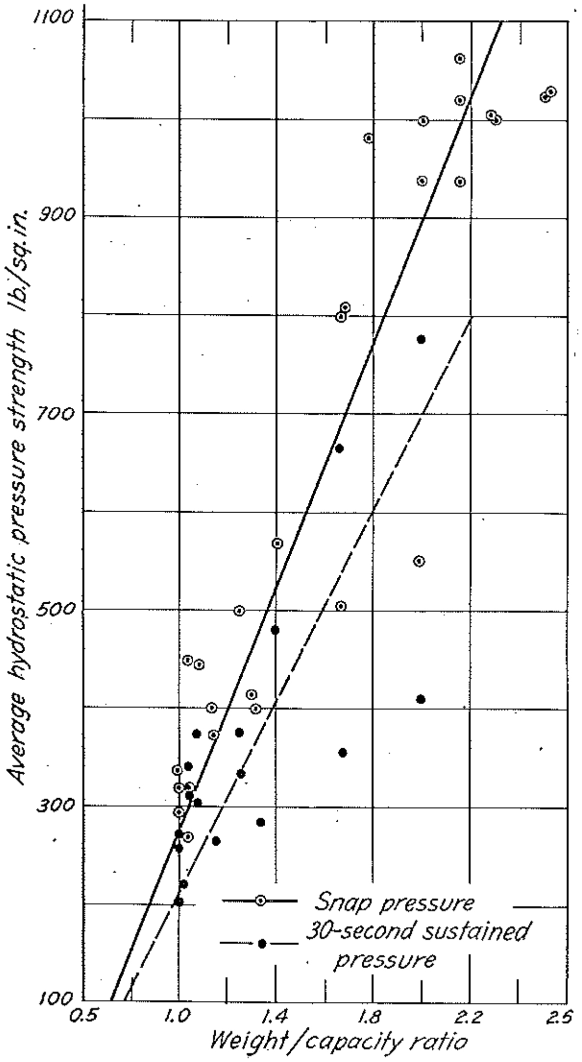

FIG. 8.—Tests on commercial gob-fed bottles.

Table III gives figures obtained on a few typical varieties.

It will be obvious at once that the shape of the bottle is important, square bottles or fancy shapes being much weaker than circular ones or those that are substantially circular, like the 10-sided siphons. This is obvious from theory as well as experiment

Of more practical importance is the observation, again agreeing with elementary theory, that thick-walled bottles are stronger against internal pressure than thin-walled ones. The important thing, theoretically, is the ratio of the wall thickness to the internal diameter. In practice, this is troublesome to measure, and the criterion used is the "weight per capacity ratio." Thus a bottle may weigh 32 oz. (empty) and be intended to hold 28 oz. of water. Its weight per capacity ratio is then 32 to 28 or 1.14. It is found, in practice, that to a first approximation, bottles having the same weight per capacity ratio tend to have somewhat similar internal pressure strengths.

The extent of this correlation may be judged from the graph in Fig. 8.

Additional data are given in Table III.

TABLE III

AVERAGE SNAP PRESSURE STRENGTH OF A FEW TYPICAL EXAMPLES OF PRESSURE WARE

Type	Capacity (oz.)	Strength (lb./sq. in.)
Club soda	3	550
	6	800
	10	568
Siphons	37	532
7 Up	6	937
Coca Cola	6	835
Ginger ale	6	795
	12	414
	23	318
	28	372
	32	293
Export beer	12	380
Steinie	12	339
	32	260
	Half gallon	176

The correlation between weight per capacity ratio (W.C.R.) and resistance to external crushing has not yet been worked out.

The correlation between W.C.R. and thermal shock strength is known to be negative for very thin-walled articles. It is believed to be zero for ordinary bottles, where the wall is $^1/_8$ in. thick or more. Adequate data are not yet available.

The practical significance of the W.C.R. is worth some discussion.

Where glass is in direct competition with other containers, it may be an advantage to make the glass article as light as is practicable. This reduces the amount of batch material required, the amount of fuel to melt it, and the wear and tear of the melting tank per container. As a rule, the forming machine can operate faster producing more bottles per minute, and the leer can run faster on the annealing. Finally, shipment to the bottling works costs less as there are more bottles to the ton. Thus there is frequently a good deal of pressure on the manufacturer to make the bottles as light as he can.

On the other hand, there are instances where a maximum thickness is desired, also for economic reasons. Thus there has been no question to date of putting Coca Cola up in anything but glass, or in any glass container except the one long since standardized. With a given external appearance, a minimum quantity of liquid is needed, if the bottle walls are made very thick. The problem is to make the package look large while the amount of beverage is kept small. The bottle is used time and time again, year after year, and its cost per filling is slight. There is, of course, no difficulty offered to the manufacturer in such cases in getting an immense internal pressure strength.

XI. The "Time Factor" in Testing of Glassware "Duration Testing," Fatigue, and Repeated Testing[*]

Until recently, it was assumed that the rate of loading of glassware was not important, though evidence to the contrary had long been available. It was none the less the regular practice to raise the pressure at an arbitrary rate, somewhat rapidly, but varying in rapidity from operator to operator and from bottle to bottle; it was tacitly assumed that the bottle would withstand indefinitely the same pressure that it withstood on this "snap" test. As a matter of fact, there is a distinct difference, and the practical justification of the "snap" test is, or was, that bottles, in all normal cases (except siphons), are so strong that even after the crude figures were corrected for the time factor, the bottle would be many times as robust as necessary. Further, if the test, though somewhat variable, were yet even moderately consistent in its manner of application, an idea might be obtained as to whether the quality of the ware were the same from day to day.

In the early days, the pressure test was not intended to warrant to the customer that the bottle was strong enough; it was known that the bottles were always amply strong. The test was applied to see if bottles were beginning to blow thin at the seams—it was a check on "distribution."

It now seems unlikely that the "snap" or instantaneous pressure test will persist, but rather that it will be discarded in favor of sustained-load testing. The "snap" test has the advantage of being expeditious; if the rate of loading is controlled, so that each bottle gets the same treatment as any other, and if it can be shown that there is a definite correlation between pressures read on the "snap" test and the strength of the bottle under prolonged load, the "snap" test may continue in use. But at present, it would seem that glasses of different composition fatigue at different rates, and it has to be shown that bottle glass compositions differ so little that the rates of fatigue are similar for all ordinary bottles. Another objection to the snap test is that there seems no satisfactory way of determining an instantaneous pressure of this sort except by a pressure gage, which is an instrument very prone to get out of adjustment and rarely reads accurately.

It has been generally believed that the law connecting observed strength with time is "logarithmic," *i.e.*, if the pressure is plotted linearly and the time logarithmically, a straight time law is obtained. For example,

$$p = A - B \log t,$$

where A and B = constants.

As a matter of fact, some series of experiments agree fairly well, or very well, with this law, and others do not agree at all closely with it. When a sufficiently long range of durations is used, it is found that the law is definitely faulty.

The advantage of finding a mathematical law that accurately portrays the facts would lie in the possibility of extrapolating to very long times. It is not the simplest of matters to subject a bottle to a constant internal pressure for a year or two, and to do it on a large number of bottles, which is necessary in order to strike a fair average, is even less practicable. The possibility that on a long-duration test something besides the mere maintaining of pressure may cause deterioration is a matter that should not be overlooked. For instance, there may be spontaneous deterioration due to slow physical or chemical changes in the glass. We know that in bright sunshine the bottle may change color and that in damp climates it may weather and decompose on the surface, so that changes in mechanical strength are not unlikely. In view of our ignorance of these matters, it can not be assumed that a long-duration test would measure only the effect of the pressure. A clear-cut law that would permit extrapolation from tests of moderate duration would be of great assistance, but it seems clear that up to the present we do not know the law and must rely on empirical data.

It is quite uncertain whether the glass has a finite strength when tested for an infinite length of time, or whether it has an infinitesimal strength under these conditions.

It is uncertain also whether the strength on a very short test is finite or infinite. It is clear that a test, to be comparable in stress distribution with a test of any moderate length, must be of such a duration as to permit the stresses to be established. This means that we are limited by the speed of sound in the bottle, and, if the bottle is loaded through the medium of an internal fluid, by the speed of sound in the fluid. A suddenly applied load merely starts pulses through the tested object, and the stresses may be entirely different from those under a static load.

Experimentally, the data available to date on bottles include static durations from a minimum of 3 to 5 seconds up to a maximum of an hour or a day or thereabouts, and even this information is rather scanty and perhaps not consistent. (The writer hopes to have information greatly extending this range in the near future.)

The data given in Table IV were obtained on bottles.

TABLE IV

EFFECT OF TIME OF TESTING ON PRESSURE STRENGTH

Type	No. tested	Loading interval (50-lb. increments to destruction)	Av. strength (lb./sq. in.)
Amber Steinies	50	Snap (2 sec.)	376
$10^{3}/_{4}$ oz. wt.	50	5 sec.	339
12-oz. capacity	30	30 sec.	323
Good commercial quality	50	1 min.	292
	50	15 min.	281
	30	3 hr.	230

The tendency of glass to break under long-continued loads, which it will stand for moderately short periods, has frequently been termed "fatigue." The term sounds appropriate enough, but the physical nature of the process is not cleared up by giving it a name. It does not appear to be analogous to the "fatigue" that engineers encounter in steel subjected to alternating stresses. It is not similar in ostensible cause, and it is uncertain whether it is fundamentally the same as a problem in physics.

On rods, the loading intervals have been successfully shortened to $^{1}/_{100}$ second and lengthened to a day or more, thus giving a wider range of static-load durations. As

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[*] December 16, 1936.

the matter is still under investigation, numerical results can not be given here.

Repeated Testing

Allied to the problem of fatigue is the deterioration of strength with repeated testing. In the case of bottles, this is most clearly seen in connection with thermal shock tests. Most bottles will withstand a thermal shock of 70°F differential, but if the test is repeated time and time again on the same bottle, sooner or later it may break. At 60°F differential, it needs many repeated tests to break 50% of the bottles; in fact, as far as is known, the test has never been repeated often enough to break 50%. At 70°F differential, a moderate number of tests will sometimes do it, and at 75° or 80°, still fewer. The actual figures vary widely with different styles of bottles.

The graphs in Fig. 9 illustrate this point.

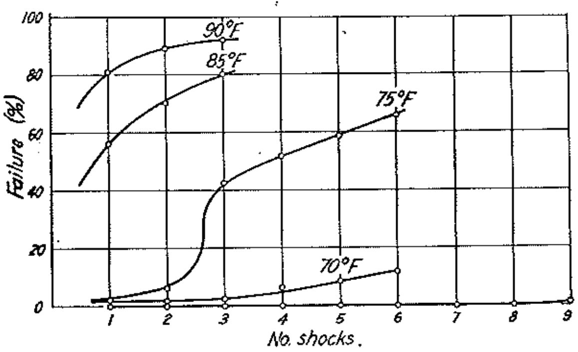

FIG. 9.—Repeated thermal shock G-102 quart ginger ales.

XII. Use of "Theory of Errors" in Expressing Results of Testing of Glassware*

It is customary, in all ordinary measurements of physical quantities, to express a result in the form 1453 ± 4, indicating that the average value of several measurements is 1453 and the "probable error" is ±4, *i.e.*, the true value has, in our opinion, a 50–50 chance of lying within the limits 1449 and 1457.

All such methods of expression tacitly or explicitly assume that the values obtained on individual measurements are distributed according to the "normal curve of errors." This means, among other things, that our measurements are just as likely to be below the true average as above it and to be in error by the same amount either way. As applied to bottles specifically, if the average strength is 300 lb./sq.in. on the internal pressure test, it means that we shall find just as many having a strength of about 200 lb./sq.in. as with a strength of 400 lb./sq.in. Carried to the limit, it means that we should find just as many with zero strengths as with a strength of 600 lb./sq.in. Finally, carried to absurdity, it means that there are a few bottles with strengths of 700, 800, or 1000 lb./sq.in. and an equal number with negative strengths.

A bottle can not very well have a negative strength, whereas bottles with twice average strength are not only conceivable but are encountered in practice.

It follows that the "normal curve of errors" can not be strictly applicable; theory alone shows that, and practical experience confirms it. The question then is how far is it out and is there some other curve or expression that fits it better?

The "normal curve of errors" is of the form

$$y = y_0\, e^{-bx^2}.$$

Where y = number of observations or measurements that fall in a given zone, Δx (between 1450 and 1452)

y_0 = number of measurements that fall in the central zone, Δx (between 1452 and 1454)

b = a constant.

The question whether our typical experience of bottles can be fitted to this curve has been investigated experimentally on several lots of bottles with one thousand bottles in each lot. Inasmuch as the original data and memoranda are available, it is unnecessary to go over them again here, but it may be said that, at present, the evidence is that the "normal" or "Gaussian curve" is not strictly applicable, but in some series of experiments it comes quite close to representing the facts and may well be used because all other expressions are more complicated and not necessarily any more enlightening.

On thermal shock tests, the normal curve is quite good, but nearly always there is enough error to produce uncertainty.

If the probable error is expressed as a percentage of the average strength, we find, on pressure testing of ordinary bottles, that the percentage is around 10% or higher, while on thermal shock testing, it is distinctly less, nearer 5%. We are not able to account for this to date, except on the assumption that the bases of bottles (where thermal shock breaks start) are more nearly alike than the barrels, where pressure breaks start.

The curve, $y = y_0 e^{-bx^2}$, may be expressed as $\log_{10}(y/y_0) = (-b \log_{10} e)x^2$, so that, if log y is plotted against x^2, the curve reduces to a straight line. For this purpose, x must be measured from the position of the mean strength as zero. In other words, x is not the strength of the bottle, but the difference between the measured strength on a particular observation and the average strength of the whole group.

Because commercial "graph paper" is not available for this sort of plotting, the student must do his own plotting, but graph paper logarithmic in one direction and linear in the other is usable. Note that log (y/y_0) is always negative, and x^2 is always positive. The graph therefore has an upside-down appearance, the x axis being along the top of the paper, and the origin at the top left-hand corner.

In thermal shock testing, the results come out in a different form. We have already indicated that bottles should be tested only once with thermal shock because repeated shocking weakens them. It is thus necessary to take a large number of bottles and divide them into a number of groups, one group to be tested at about 70°F differential, the next at 72°F, the next at 74°F, and so on. Out of each group, a certain percentage will break, and it is to be expected that the percentage breaking will increase with the severity of the quench, until finally at perhaps 100° or 110°F differential all the bottles break.

The measurement thus obtained (expressed as a percentage of bottles breaking) is not the y of our previous equation, but $\int_0^T y\, dT$, where T is the thermal differential measured from zero.

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* December 19, 1936.

To make the equation usable, we have to refer it to that differential T_0 which breaks 50% of the bottles as the zero of x, and the measured quantity is then

$$\frac{\sqrt{b}}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-bx^2}dx.$$

What is actually given in the Smithsonian Physical Tables of the "probability integral" is equivalent to

$$\int_{0}^{x} e^{-bx^2}\,dx,$$

expressed in such a form that

$$\frac{\sqrt{b}}{\sqrt{2\pi}}\int_{0}^{\infty} e^{-bx^2}\,dx = \frac{\sqrt{b}}{\sqrt{2\pi}}\int_{-\infty}^{0} e^{-bx^2}\,dx = 1.$$

Under these conditions, the integral in which we are interested, *viz.*,

$$\int_{-\infty}^{x} F(x)dx = 1 - \int_{x}^{0} F(x)dx \text{ or } 1 + \int_{0}^{x} F(x)dx,$$

according as x is negative or positive, *i.e.*, according as we are working below or above the average bottle strength.

In the Smithsonian Physical Tables, for instance (p. 56, 1921 edition) will be found tabulated values of the integral,

$$P = \frac{2}{\sqrt{\pi}}\int_{0}^{hx} e^{-(hx)^2}\,d(hx).$$

The maximum value of this integral, *i.e.*, the value $\frac{2}{\sqrt{\pi}}\int_{0}^{\infty}$ is unity, and similarly $\frac{2}{\sqrt{\pi}}\int_{-\infty}^{0}$ is unity, corresponding to our co-integral value of 50%.

The student should practice the use of the table on his own data. If he does, he will discover to what extent the experimental results of thermal shock tests fit the supposition of Gaussian distribution.

The Gaussian curve may be derived from the binomial expansion coefficients of such a formula as $(1/2+1/2)^n$, and while it may express sufficiently well the probability of any configuration of heads and tails or a combination of n coins picked up at random, there is no sound reason known to us why it should express the strength of bottles, and there are good reasons why it *should not*.

If, in any particular set of experiments, the normal or Gaussian distribution does not hold, it may become necessary for the student to investigate it on a more general basis.

It is wise, first, to make sure that the testing apparatus is free from avoidable error, and still more, to ascertain that the bottles represent a "homogeneous population." If, at the end of the leer, some of the bottles are unpacked two at a time and rubbed on each other and others are taken out one at a time and covered with perspiration, grease, oil, or dirt of any kind before they are allowed to touch, we shall have two kinds of bottles, and the distribution will be bimodal. If the curve is plotted, this will be obvious if the two kinds are present in comparable numbers; the plot of the frequency curve will merely appear skew with a long tail on the high-strength end.

For a discussion of the whole subject and for means of determining whether a frequency distribution can properly be treated as Gaussian or not, see Elderton.[23] In particular, calculate the quantities on p. 53 thereof, and determine the discriminants. It is well to do this in any case before assuming that the Gaussian curve applies.

XIII. Variation of Strength with Temperature*

This chapter, with the unlucky number, has the ill-luck to be about a subject on which little is known with any certainty. Over the range of temperatures to which bottles are normally subjected in use, *viz.*, from ice-box temperature (35°F) to the heat of a hot day (100°F) or pasteurizing temperatures (150°F), there is little reason to expect any appreciable change in strength, though such changes have been reported.

Tests have been made on the strength of plate glass at various moderately elevated temperatures up to several hundred degrees Fahrenheit, and slight increases and decreases of strength were reported up to the time the glass begins to soften (900° to 1000°F). The difficulty with these tests is that the change in strength can not be measured on the same article as are changes of elasticity, refractive index, or most other properties; we have to destroy the specimen to measure its strength. When we try to measure the strength by testing comparable specimens, great uncertainty exists as to how far the specimens are alike, and it becomes necessary to test a considerable number of specimens at each temperature and to compare the averages. But a good deal of uncertainty may still persist as to the reality of the differences between averages, on account of the larger variations in individual strengths and the apparently slight differences in the average strength with temperature.

In the case of mild steel, or most other metal, there is a pronounced change of strength with temperature, the strength usually falling rapidly after a moderate rise of temperature. This change, however, corresponds in nature to the softening of glass above the annealing point and not to such changes as we expect to see at lower temperatures.

Some light is thrown on the subject by measurements of Young's modulus. These can be carried out with great precision, and the work has been done at Corning, N. Y. Definite, but relatively slight, variations are found. It follows that if glass breaks at constant strain, then the stress must vary at different temperatures. If the stress is constant, then the strain must be variable. The remaining possibility is that both stress and strain at the breaking point vary with temperature.

It would seem wise to try to determine the strength at very low temperatures, *e.g.*, those of liquid air, in order to extend the range downward, and it would seem easier to do this for rods than for bottles.

Tests made here on the strengths of bottles over the range of practical interest show that as far as bottles are concerned, the effect of temperature is unimportant compared with the other variables. It is also far from certain that temperature alone was responsible for the observed effects.

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[23] Frequency Curves and Correlation. Chester and Edwin Layton, London, 1927.

* December 21, 1936.

XIV. Theory of Bottle Strength under Internal Pressure Test[*]

If the bottle be cylindrical and the wall relatively thin, the tensions in the wall are substantially the same throughout the thickness of the wall. The principal tensions are axial and peripheral in direction, and the peripheral is twice as great as the axial. The theory is the same as in the conventional treatment of the steam boiler problem.

$$\text{For peripheral tension, } f = \frac{p}{2} \cdot \frac{d}{t}. \qquad (1)$$

$$\text{For axial tension, } f = \frac{p}{4} \cdot \frac{d}{t}. \qquad (2)$$

Where p = internal hydrostatic pressure
d = diameter of bottle
t = wall thickness.

The third principal stress (in a radial direction) is a compression, but is assumed to be negligible.

When the wall thickness is not small, the theory of thick cylinders applies. There is some evidence that for stouter bottles, the more accurate theory should be applied. The theory indicates that the peripheral tension, which is the important one, is then not uniform throughout the wall thickness, but is much higher on the inside than on the outside. This is convenient, because the inner wall is much stronger than the outer one and can stand the extra stress.

At any radius, r, between the limits, $r = b$ (outside radius of cylinder) and $r = c$ (inside radius).

$$f = p \cdot \frac{a^2}{b^2 - a^2} \cdot \left(1 + \frac{b^2}{r^2}\right). \qquad (3)$$

At the outer face,[†] $r = b$.

$$\text{Therefore, } f_1 = 2p \cdot \frac{a^2}{b^2 - a^2}. \qquad (4)$$

At the inner face, $r = a$.

$$\text{Therefore, } f_1 = p \cdot \frac{a^2 + b^2}{b^2 - a^2} \qquad (5)$$

In expressions (4) and (5), b and a are, respectively, the outer and inner *radii* of the bottle, but obviously the expressions will not be changed if we take them to be the outer and inner *diameters*, respectively. (6)

In practice, we always find that the bottle breaks from the outer face, although f_1 is there the smaller. It would be interesting to have bottles made of so great a wall thickness that the crack would start on the inside. This would give an idea of the relative strength of the inner and outer walls.

For the Theory of Thick Cylinders in detail, see any text on the theory of elasticity.[24]

Bottles with Eccentric Bore

There are many bottles which blow unevenly and become thin on one side. In the case of thin cylinders, it will suffice to take t as the minimum wall thickness.

In the case of thick cylinders, the expression is quite complicated (see Timoshenko,[24] pp. 57–58).

Bottles with Elliptical Bore

Probably more serious is the case, even with thin-walled bottles, when the bore is not circular. It often approximates an ellipse. The outer surface may be circular and elliptical, and the inner and outer ellipse may be oriented parallel or otherwise. The bending stresses set up when the inner wall is elliptical and the outer is circular, or when it is elliptical but the wall is of uniform thickness, might well be a subject for mathematical exercise. As far as the writer knows, they have not been worked out, though the "Bourdon" gage, used in practically all pressure gages, employs the swelling of an elliptical tube toward a more circular shape to effect the measuring of the pressure.

Effect of Shortness of Cylinder

All, or nearly all, bottles, instead of being the infinitely long cylinders envisaged in the theory, are short and derive some support from the base and the shoulder. The practical effect of this has been examined by special polariscopic arrangements and was found to have a pronounced bearing on the proper design of bottles.

Strength of the Bottle Base

The base of a typical bottle is substantially a circular disk, fairly flat, subjected to uniform hydrostatic loading. (The complicated expressions for the principal stresses will be found in Timoshenko, p. 317.) To these expressions must be added an additional radial term due to the stretching of the base by the hydrostatic pressure on the side walls. In addition, we have the complication that, in practice, the base of a bottle varies somewhat in thickness and tends to be thicker in the middle than elsewhere. It is doubtful whether we can even approximate the actual stresses by any calculation, but it might be well to try to estimate their magnitude, inasmuch as in some recent bottles there is a tendency for the crack to begin in the center of the base.

Strength of the Neck

Up to date, we have not observed in an ordinary uninjured bottle, any tendency for a pressure break to start in the neck, though many instances have been observed where cracks started in the neck by other agencies have been developed into pressure breaks by the internal pressure action.

Strength of Noncylindrical Bodies

When the barrel part of a bottle instead of being cylindrical is truly barrel-shaped, as in club-sodas, a great deal of extra strength is conferred upon it. A hollow sphere is twice as strong as a hollow cylinder of the same diameter and wall thickness (when the wall is thin), and therefore we should prefer a spherical shape.

This has the advantage that it is the most "natural" shape for a bottle to take; in other words, we blow the bottle in the first instance by internal pressure, and if left to itself, it would form a sphere, which is the shape most resistant to the pressure. A spherical shape, moreover, tends to give a uniform wall thickness.

Club-sodas are abnormally strong bottles, but they are troublesome in the bottling process, and the makers of bottling machinery do not like them. They are also indifferent articles to pack, taking up a lot of space; otherwise, they might be the best form for lightweight containers.

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[*] December 21, 1936.

[†] Unless the bottle has been damaged internally. Capillary tubing, according to Littleton, breaks from the inside, as is to be expected.

[24] S. Timoshenko, Theory of Elasticity, p. 56. McGraw-Hill Book Co., 1934.

XV. Theory of Thermal Shock*

Various attempts have been made to express the resistance of glass to thermal shock in terms of the fundamental physical and geometrical properties of the glass. Thus it is clear that the resistance of the glass will vary with Young's modulus, E, the coefficient of thermal expansion α, and the tensile strength of the glass, f_t. Unfortunately the latter quantity is known to vary with the duration of the test (see Part XI, p. 17), and it may vary with the extent of the skin-depth subjected to the tension; both of these things are beyond control in an ordinary thermal shock experiment. In a very massive piece of glass, initially at uniform temperature and plunged into a liquid maintained at some lower temperature, the depth of the surface zone subjected to tension increases steadily with time, and both the fatigue effect and the depth effect might be expected to produce an increasing likelihood of a long-delayed fracture the longer the experiment was continued.

In practice, thermal shock tests are carried out on glass bodies of limited extent, thin rods, usually no more than $^1/_4$ inch in diameter, or bottles with walls no more than $^1/_4$ inch thick. With such test objects, fracture occurs in a matter of 2 or 3 seconds, and if the glass is not then broken, it does not break at all. It is worth noting, however, that the fracture is not instantaneous upon quenching.

This means, among other things, that it is most likely the thermal diffusivity of the glass must be taken into account, which has been done in the Winkelmann and Schott formula; the formula, however, is dimensionally unconvincing, and does not seem to have been verified in any conclusive way by experiment.

In the case of thin specimens, the thermal differential necessary to break the glass will clearly go up as the thickness goes down, and on the simplest theory, in the case of bottles (where the inner face is maintained hot) reaches a value twice as high as for very massive-walled articles. According to other theories and in practice, greater variations than this are met with.

Hampton indicates that an empirical rule is that the temperature differential needed to break a beaker (his favorite test object) is inversely proportional to the square root of thickness. This means that when the glass gets very thin, the strength is infinite, though it would appear that the skin stress should not be reduced below half that for massive glass. Evidently, we are here dealing with some conditions that can not be described in terms of a static theory of elasticity.

In all the theorizing that has been done to date, it seems to have been assumed that there is a physical quantity, resistance to thermal shock, which is a property of the glass alone and exists as it were in empty space. A thermal shock experiment, however, always involves a quenching medium as well as an article to be quenched, and the result obtained is a property of the whole experiment. It is known that the differential required to break the bottles varies greatly with the quenching medium used, being least with water, greater with ethylene glycol, glycerine, and oil.

The following results by Dr. Hunter indicate the trend:

Water	120°
Ethylene glycol	237°
Glycerine	242°
Lubricating oil	323°

It may be that the results of a thermal shock experiment can be expressed in such a fashion that the properties of the liquid and the properties of the glass occur as entirely separable factors, and that is the basis of all existing theories, but no one has proved either theoretically or by experiment that it is so, and very likely it is not so.

(For instance, suppose there is a property, A, of glass, possibly diffusivity or some more elaborate affair, which opposes fracture, and a property, B, of the liquid that tempers the severity of the cooling. The results of the experiment, *i.e.*, temperature differential needed to produce fracture, will be a function of the form $\phi(A,B)$. If $\phi(A,B)$ is of the form A^xB^y, the variables are separable, but if $\phi(A,B)$ is of the form $\phi(A+B)$ or $\phi\left(\frac{1}{A}+\frac{1}{B}\right)$, the variables are not separable.)

We may ask what properties of the liquid will tend to facilitate sudden cooling, or to reduce it, but as soon as we start to formulate a theory, we perceive that the important qualities may differ according to where the experiment is performed. Thus the result may be different according as we imagine the experiment carried out on the earth's surface or in interstellar space. Heat may be taken from the bottle to drop its surface temperature by two methods, (1) convection in the liquid, or (2) conduction through the liquid. (Radiation losses will be too slow to produce appreciable chilling.) Convection currents depend on the action of gravity to start them and will not take place in interstellar space, where the local value of gravity is negligible. This is not an entirely academic point, for the factor resisting gravity and keeping the convection currents within bounds is viscosity, and if the value of the viscosity is high enough, the local value of gravity on the earth may be too low to produce appreciable convection. This might obviously be true if we tried to quench the bottle in thick pitch, and it may be true if we use thick oil. On the other hand, if viscosity is very low, as in alcohol, we may perhaps find that convection currents are important.

But gravity can not produce convection currents in a liquid that does not expand with heat; thus, if convection is an appreciable factor in quenching bottles, we must take account of the coefficient of thermal expansion of the *liquid*, as well as of the glass.

Finally, we can not quench a bottle in still liquid; the act of quenching starts up in forced convection or swirling as we plunge the bottles into the liquid, and this stirring of the liquid is usually much more forcible than the natural convection set up by the collaboration of gravity and the thermal expansion of the liquid. Thus if convection is the main factor in quenching the glass, the problem in practice boils down to that of producing a known measurable and expressible artificial convection. It is the quantity (mass) of fluid that can be circulated past unit surface of the glass in unit time multiplied by the specific heat of the liquid that should determine the severity of the quenching.

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* December 22, 1936.

Plant operators and testing men have usually been in the habit of giving their bottles a swirl in the quenching medium to make the test more severe, and Murgatroyd recommends running water in a trough, but the velocity of swirl or of contact is not usually known. It is believed that these additional aids to quenching are proper, but they are clearly arbitrary unless it can be shown that no additional swirling or velocity of current will make the test any more severe.

A fuller discussion of the theory of thermal shock is given in a separate paper, not yet published, but accessible through private communication.

In a bottle of "ordinary" proportions (such as an "export" beer or a typical "soda"), internal pressure tests the side wall strength, and the fracture begins there. Thermal shock, on the other hand, usually tests the strength of the base. The base, for this purpose, includes the "Murgatroyd belt," a narrow peripheral band at the base of the side wall below the range normally vulnerable to pressure testing.

The things that usually make a bottle weak on thermal shock testing are (*a*) excessive cord, (*b*) poor cut-offs, (*c*) buried baffle marks, (*d*) bruises and scratches on the Murgatroyd belt, and (*e*) poor design of junction of side wall and base.

All of these subjects are a little complex. The mathematical theory covering (*d*) and (*e*) has been worked out in some detail by the present writer (not yet published) and is undergoing a good deal of experimental investigation.

XVI. Theory of the Polariscope*

This subject, fortunately, has already been dealt with in a manner suitable for students of glass technology.[25] This covers the whole subject, except the problem of grading bottles in a commercial fashion.

It is usual to grade bottles by the appearance of the base, as seen by peeping axially down through the neck. Temper (1) (Glass Container Assn. Standard Grading of Annealing Disks) bottles are sensibly of one color throughout. In temper (2) and (3) bottles, there are three colors, as recognized by an average observer. The central parts are field tint (usually a purple, if a sensitive tint plate is being used and the bottle is of colorless glass); two quadrants verge toward blue at the margin, and the other two toward orange. In temper (4) bottles, each quadrant has two recognizable colors as judged by an average observer, and the zone of field color is beginning to take on the form of a recognizable cross. In temper (5) and temper (6) bottles, the cross is conspicuous, and the quadrants are brilliantly illuminated with a rainbow of colors.

In bottles of colored glass (emerald green, dutch green, amber), the absorption of light in the base is so high that the glass color predominates over the polariscope colors, and the sharpness of the cross becomes the main discriminant. For this purpose, the tint plate is best removed, and the cross then becomes black.

The cross arises, of course, from the fact that ordinary polariscopes use plane polarized light; in circularly polarized light (which is used in a good many photoelastic polariscopes, following a suggestion of Silvanus Thompson to Professor Coker) the cross disappears. The cross is due to the fact that the stresses in the glass coincide in direction in these zones with the direction of the plane of polarization and produce no optical effect which is independent of their orientation, so that the base of the bottle appears as rings of color surrounding a circular central spot of field tint.

After examining the possibilities of such an arrangement, we believe the cross will be found useful.

It is advisable to attempt the grading of the sides of the bottles as well as the base. In general the sides of a bottle are better annealed than the base, but complex stresses are sometimes set up by having the bottles too close together in the leer, thus impeding the convection currents of air which do most of the annealing.

Very rarely bottles will be found that are annealed sufficiently in both base and sides but have the neck highly strained.

An accurate measure of these phenomena can be obtained in the immersion projecting polariscope, using carbon tetrachloride for the immersion medium and a Babinet compensator in the eyepiece. The student should practice its use.

Use of Grading Disks (G.C.A. Standards)

The grading of bottles by their polariscopic appearance is very much a "subjective" business; it depends on the observer's color vision and upon his psychology. On the "objective" side, it depends on the color of the light used and also on its intensity. Thus, some firms have found it well worth while to throw out the illuminant supplied by the manufacturer of the earlier types of polariscope and put a gigantic kilowatt bulb in its place. The sensitive tint plate, which we prefer to have 565 millimicron retardation, is often far from it, and as the plate is sensitive to its own thickness, the color varies from polariscope to polariscope even when the illuminant is standardized and the operator can be considered to have normal color vision. The G.C.A. grading disks have an accurately standardized retardation and reproduce the appearance of a bottle bottom. This is possible by reason of the fact that in any symmetrically strained circular object, the retardation at a distance, r, from the center must be of the form $\bar{\mu}$ or $\Delta\,\mu = Ar^2 + Br^4 + Cr^6 +$ etc., and in most cases to the first approximation, $B = C = 0$. This is very nearly true of the G.C.A. disks. Bottles are more variable, but allowing for the limitations of the human eye, the comparison of the bottle with the disks presents no serious problem. Because the disks are themselves colorless and are used for comparison purposes by a particular operator in his polariscope, the uncertainty that attached to the old *A*, *B*, and *C* gradings is eliminated.

Use of Polariscope for Estimation of Cord

All commercial bottles tend to be slightly cordy, and this is true of handmade bottles imported from Europe just as much as of the product of the high-speed machinery of America. In general, it appears that cord can become quite conspicuous in the polariscope without affecting in any measurable way the properties of the bottles. At a somewhat uncertain point, cord becomes "excessive," and thermal shock strength drops off. The bottles may also show weakness under long-continued hydrostatic

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* December 22, 1936.

[25] See footnote 7(*d*).

pressure, as if they had a high fatigue rate. No correlation, however, has so far been found between fatigue and degree of cordiness over a very wide range of the latter, though extensive and painstaking work has been done on the subject.

We are obliged to conclude that the use of the polariscope as a criterion for cord is at present restricted to that of a warning device. If cord begins to become noticeable or conspicuous, further tests, especially thermal shock tests, are advisable to see whether or not the cord is affecting the working properties of the bottle.

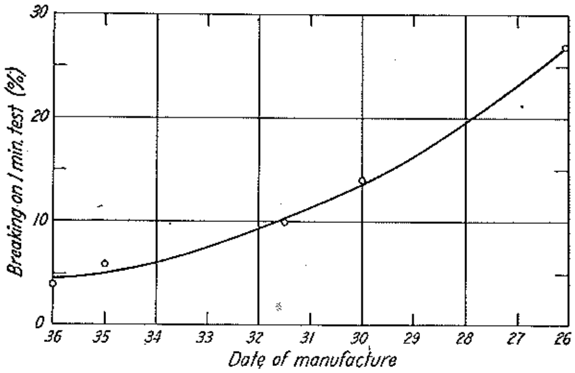

FIG. 10.—Example of deterioration of bottle strength with age and abuse; used Coca Colas tested at 400 lb. per sq. in.

It is possible that the only satisfactory way of estimating cord is by ring-section cutting. A few firms with substantial experience think well of this method, but at present the test remains qualitative and a matter of individual skill. A great deal more information on the subject is likely to be acquired in the near future.

Use of Polariscope for Measuring Stresses Set Up by Internal Pressure or Thermal Differential

The projection immersion polariscope may be used to determine the relative retardation at all points in the median plane of a bottle subjected to internal pressure. This has been done, with the aid of a little theory to help out the experimental data, for siphon bottles. In the same way, it should be possible, by circulating a warm fluid inside the bottle and a cold fluid outside, to estimate the stresses in the important regions of a bottle undergoing thermal change. In the case of thermal shock, however, where we are dealing with transient stresses, special arrangements, possibly kinematographic, would have to be made.

XVII. Deterioration with Age*

Bottles do not keep their pristine strength in practice. There is reason to believe that the deterioration may be due to more causes than one. Logically, we may expect that the mechanical abuse they get in practice is the main cause of the falling off in strength, for the outer surfaces get badly battered and sometimes the inside gets scratched.

It is possible also that "weathering" has an effect, but perhaps only when combined with battering. James Bailey has shown that small fissures are opened up and propagated by a weathering process, the decomposition products of the glass wedging open the fissure and causing it to extend. The same thing has been observed by L. T. Sherwood in the deterioration of wire-glass skylights in sulphite pulp mills.

On the other hand, it is possible that weathering alone may effect some deterioration.

Again, solarization may affect the strength. We know that bottles decolorized with manganese may be rendered a brilliant purple by the action of bright sunlight over a prolonged period, and if the color can be changed, there is no obvious reason why other physical changes should not go on in the glass, including a change of mechanical strength. It seems improbable, however, that the average bottle gets enough solarization to effect marked changes.

FIG. 11.—Polaroid polariscope.

Tests made in this laboratory on weathering and solarization, much more severe than a bottle will usually encounter, show no measurable difference.

Finally, bottles in use go through a series of thermal cycles, often abrupt, in their washing, filling, and pasteurizing. These changes are not sufficient under normal conditions to break the bottle, but they may conceivably assist in extending existing minute cracks just as weathering does. Such a result would be expected.

In any case it is observed, as a matter of practice, that if bottles of a particular pattern (size, shape, weight, etc., identical), of the same color, and substantially the same composition of glass but of different years of manufacture, are obtained out in the trade, they are found on testing to show a progressive weakening with age. This is in spite of the fact that the weakest bottles of the older vintage have been broken and thrown away, and only the

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* December 22, 1936.

fittest have survived. It seems scarcely possible that processes of manufacture have improved so much and so consistently that the strength of the newer bottles is due to causes other than the youth thereof, and we must apparently accept deterioration with age as a genuine fact.

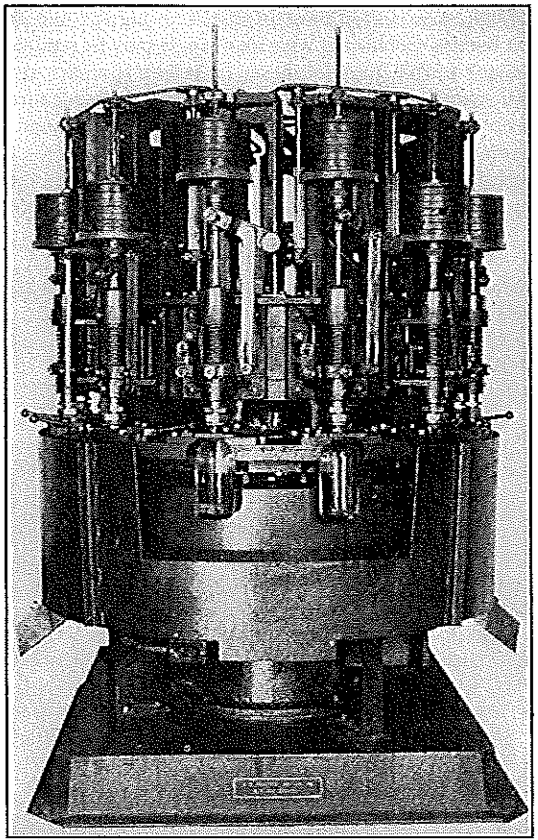

FIG. 12.

This, of course, raises serious questions as to how long a bottler should continue to use his bottles without giving them a test for strength. Many of the bottles involved in our lawsuits are of very ancient vintages.

A characteristic curve of strength *vs.* age, by Dr. Hunter, is given in Fig. 10.

Data on the causes of the deterioration are yet scarce. For example, we have found some deterioration in strength between the manufacture of a bottle at a plant and the time it can arrive in Butler for testing. This might be due to rough handling in transit.

The whole subject needs further experimentation.

XVIII. Recent Developments in Testing Apparatus for Glass Containers

Some years ago F. C. Flint said to the present writer, "It wouldn't hurt any of us to know a little more about our bottles." As a matter of fact, a good deal has been learned since then, and this work outlines some phases of it. The subject of the mechanical properties of glass is much more active than it was a few years ago, not only in the container field but also in the flat glass field, and the proportion of papers in the scientific press tends to grow continually. All that has been said in this paper relates to mechanical properties in some form or other, and yet clearly merely touches the surface of things.

Naturally there are needed from time to time new species of testing apparatus for research purposes, and the country is getting full of them, but we are concerned here only with a few pieces of apparatus which seem headed for general adoption in commercial inspection and testing.

Routine of Inspection (and Testing)

All bottles are individually inspected at the cold end of the leer for a great variety of defects that only a trained human eye can catch. These involve such things as imperfections of shape, imperfect blowing of the lettering, rough necks, unlevel finishes, cracks, large stones, and other disfigurements, "chicken roosts" and other unintentional adornments, and much besides. The inspector may also notice excessive "seed" (fine bubbles), blisters, and other defects that go back of the forming machine to the tank operation. He may, by the sound of the bottle, detect these spots, but in general he can not tell all about the factory operation by merely *looking* at the bottle. The detailed behavior of the leer, forming machine, feeder, tank, and batch-mixing plant must be ascertained in the finished bottle by other means. As a rule, this is done by sampling, a modest number of bottles sufficing to check up on these points if the tests are properly run.

Inspection in Polarized Light

This "test" should come first, as the bottles are not normally affected in any way by this inspection. Some firms use an immersion type of polariscope, originally designed by F. C. Flint and later made by the Simplex Engineering Company. Many use the large field type designed by C. D. Spencer and later made by Simpson Engineering & Foundry Company. The coming of the Herapathite film, devised by E. H. Land and made by the Polaroid Corporation, has led to the development of a polariscope that has the inherent advantage of giving a large, uniform, and intensely illuminated field without using complicated optical systems (lenses, condensers, prisms, and Nicol prisms). Present indications are that the Polaroid type of polariscope will be widely used in the future for the examination of bottles. Figure 11 shows a Polaroid type polariscope adapted to the examination of bottles.

Whatever kind of polariscope is used, however, it should have a high intensity of illumination, and the standard G.C.A. disks should be used to record the "temper." This designates the type of leer operation fairly well.

Cordiness should be observed as a check on tank operation.

Size, Weight, and Capacity Testing

The same testing department will probably handle this problem, though it does not normally concern the mechanical properties of the ware. Further, these tests are commonly carried out on unannealed ware which has not gone through the leer at all, in order to get a report on the geometrical fitness of the bottle without delay. Thus this ware can not be used for any other purpose and forms no part of testing the finished ware.

These tests concern such things as whether the bottle will fit its cap, whether it will hold the correct amount of fluid (a matter sometimes regulated by law), and therefore whether it has the correct amount of glass in it. It is thus a check on the operation of the forming machine, the molds, and the feeder.

Internal Pressure Testing

Bottles should be tested for internal pressure strength if they are called upon, in practice, to stand internal pressure. Some other sorts of ware, such as milk bottles, are also frequently tested.

The "strength" of a bottle under internal pressure depends upon the duration of the pressure, as well as on its intensity. A bottle will not hold for 1 minute as much pressure as it will hold for 1 second, nor will it hold for an hour as much as it will hold for a minute, or as much for a day as it will hold for an hour. The difference in strength between 1 second and 5 seconds is considerable, and because most of the older pressure testing was done as a "snap" test (*i.e.*, the pressure was raised quickly and at an unknown and arbitrary rate to the breaking point), there was no real knowledge as to how much pressure the bottle would stand for a month or a year.

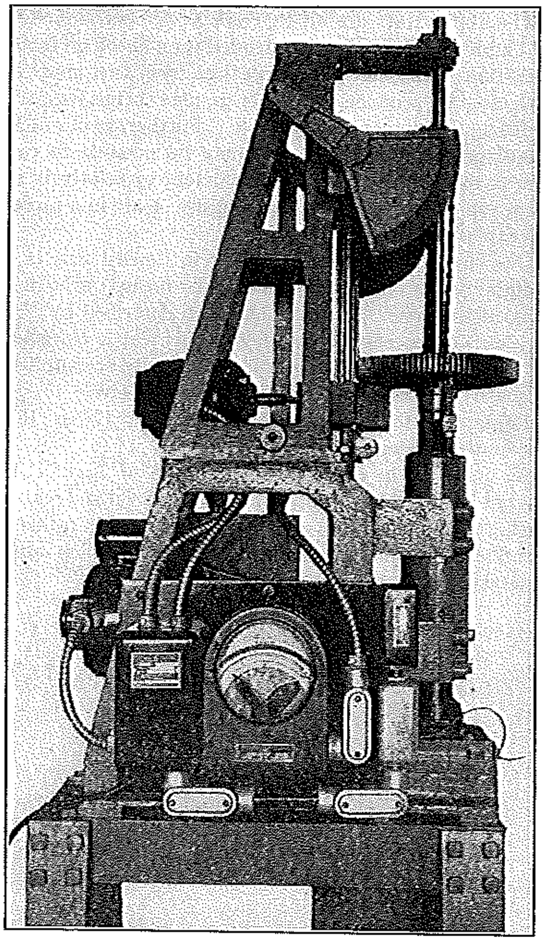

FIG. 13.—Preston automatic single-head sustained pressure-testing machine.

There are two ways of getting over this difficulty, *viz.*, (1) to use a "snap" test in which the pressure is raised mechanically in a uniform and consistent manner to the breaking point, and (2) to use a constant pressure for a definite length of time (1 minute) to see whether or not the bottle breaks. In some cases, perhaps most, the best test is to make sure that all bottles will pass a test, maintained for 1 minute, involving a pressure 50% higher than the bottle is expected to stand in practice. It is not necessary to break the bottle.

The bottles that were used for the polariscopic examination may be used for the internal pressure testing, and if they do not break (as normally they do not) they may then be used for thermal shock testing.

Figure 12 shows a 12-head testing machine giving, each minute, 10 bottles a test of one-minute duration.[26]

Six-head and four-head testing machines on the same principle are also made.

Figure 13 shows a single-head sustained testing machine equipped with automatic timing for a test of one-minute duration. These machines are normally constructed to give any pressure above 100 lb./sq. in. and not exceeding 400 lb./sq. in. in stages of 25 lb./sq. in.

Thermal Shock Testing

After the bottles have passed their internal pressure test (at the necessary test pressure for that type of bottle), the water is emptied out, and they are loaded into the thermal shock testing apparatus.

The past practice of the industry has been to test wide-mouth jars, ketchup bottles, etc., by a hot-pour test, which simulates the use the bottle will get in practice. For this purpose, boiling water is poured into the cold bottle. Up to date, this test has not been standardized in detail, and it seems likely that it can perfectly well be superseded by the more ordinary variety of thermal shock test which consists in immersing the empty bottle in hot water and then transferring it to cold water. Both in this country and in Europe, it has been a common practice to empty milk bottles of the hot water before plunging them into the cold, but this was not done with narrow-necked ware, as it took too long and let the glass cool too much.

The most important factor in determining the outcome of a thermal shock test is the differential of temperature between the two baths, but other factors have to be watched. Thus water is always the quenching medium, but the properties of water vary with temperature; therefore the *absolute* temperature of the cold bath (not merely its *differential* from the hot bath) is significant. The time elapsing in transfer between the two baths is important and must be standardized. The degree of agitation of the baths, the depth of immersion, and so on, make a difference. Obviously, the time the bottle stops in the hot bath is important. Because the bottle promptly fills with hot water in the test as hitherto conducted and the bottle at that moment is cold inside, the internal water chills a few degrees, and it is not possible to reheat it completely within any reasonable length of time. The extent of the reheat is therefore arbitrary, but it must be the

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[26] An earlier version of this machine was described in *Glass Industry*, May, 1936.

same on all tests. As a result of experiments, we have standardized in our practice on a 5-minute soak in the hot bath.

The automatic thermal-shock machine is shown in Fig. 14. It consists of two tanks, one containing hot water and the other cold. The temperature controllers at the top of the panel not only indicate the temperatures but, by connections with solenoid valves, they also maintain the proper temperatures automatically. The water in the hot tank is circulated continuously by an electric pump (lower left-hand corner) through a couple of gas-fired hot-water heaters. The cold water is also in constant circulation. The *A*-frame between the tanks, behind the control panel, carries a motor-driven crank, from the end of which the basket of bottles is suspended by a parallel link motion, which therefore keeps the basket level at all times.

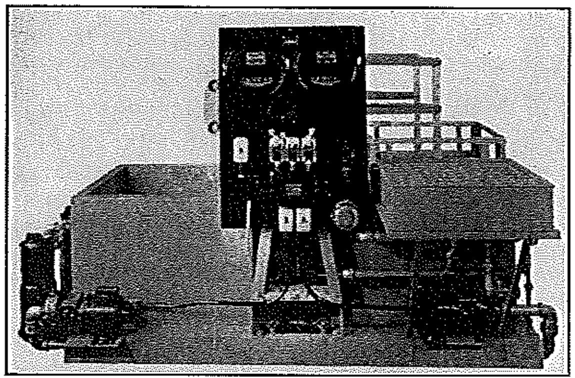

FIG. 14.—Preston automatic thermostatically controlled thermal-shock testing apparatus.

When the bottles have been loaded into the basket at a point just clear of the water in the cold tank, the starting button is pushed, and the basket moves into the hot water and submerges. At the end of 5 minutes, it automatically starts on its return trip, and in 15 seconds of transfer time it reaches the cold bath into which it plunges and dwells for 30 seconds. Thereafter it automatically lifts to the loading position, draining off the external water, and awaiting the operator, who in the meantime has been going about other tasks.

The operator at his convenience takes out the bottles one by one and inspects them for cracks; for whereas an internal pressure break destroys the whole bottle and leaves nothing but fragments, a thermal shock test usually produces a simple split. Normally, it is enough to let the water out of the bottle and so betray its presence, but not always; therefore the bottles must be inspected.

The recommended differential on the shock test is 75°F, with the cold bath at 70°F, and the hot bath at 145°F.

Other Tests

The above tests are all that are at present sufficiently well understood to be recommended for a check on factory operation. To deal with complaints from customers and with troubles produced by the customers themselves, some additional equipment is advisable. Further, as our understanding of tests improves, it may be possible to catch trouble in an early stage of development by relatively new tests, some of which are already in use or are in a more or less experimental stage.

One such test, which is already in limited use, is the examination of cord in ring sections by means of the polarizing microscope. This test has been described by V. C. Swicker. A necessary auxiliary to this test is equipment for cutting the ring section. This is usually accomplished by means of a thin abrasive cutting wheel or saw.

Equipment for impact testing (see Part IX, p. 13) is also under development.

As indicated in the second paragraph of Part XVIII, it is not intended to give descriptions of special and research testing equipment for glass containers, but rather to describe only those tests and equipment which are in general use.

BUTLER, PENNSYLVANIA