[Reprinted from The Journal of The American Ceramic Society, Vol. 42, No. 11. November, 1959.]

# Strength and Static Fatigue of Abraded Glass Under Controlled Ambient Conditions: I, General Concepts and Apparatus

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**An extensive experimental study of the factors affecting the tensile strength and static fatigue of bulk glass has been conducted. To minimize the effects of past history of the specimens, all specimens were subjected to a controlled, reproducible surface abrasion. Time, temperature, and chemical environment were subject to control and systematic variation during the period from abrasion to test and during the strength test itself. Specimens consisted of flat laths tested in cross bending with the abraded spot in the center of the tension face. An electronically controlled electromagnetic tester permitted applications of pulse loads or constantly increasing loads with controllable durations from about 0.0025 second up to any desired value. The apparatus and methods for producing the abrasions, controlling the environment, and performing the tests are described in this paper. A brief review of the experimental background on the strength of glass is also presented as an introduction to the aims and concepts of this study.**

## I. Introduction

ALTHOUGH considerable experimental work on the strength of glass has been reported in the literature, the results are in general difficult to interpret and those of different observers fail in some cases to agree with each other. Much of this difficulty arises from the inherently complex nature of the subject and the multiplicity of variables which can affect the result of a strength test. The physical and chemical condition of the surface of the specimens as determined by their previous history, the ambient conditions during test, and the type and duration of loading employed can all play important roles.

Although in previous experiments some of these variables have been recorded or controlled, seldom, if ever, have they been known to the extent necessary to permit a complete, unambiguous interpretation of the results. The aim of the research program to be reported in this and subsequent papers has been to conduct an experimental investigation of the strength and static fatigue of glass in which all the foregoing factors are subject to control and systematic variation. It was believed that the results of such a study would lead to a more complete and systematic understanding of all the factors affecting the strength of glass than has been possible heretofore.

Presented at the Fall Meeting of the Glass Division, The American Ceramic Society, Bedford, Pa., October 18, 1957. Received January 2, 1959; revised copy received June 16, 1959.

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This paper, which is the first of a series describing this work, presents a brief summary of current experimental knowledge of the strength of glass and a description of the apparatus and methods employed in the present study. Subsequent parts will present the results of specific phases of the investigation.*

## II. Experimental Background

The various experimental conditions and variables which can affect the strength of glass will each be discussed briefly in turn. No attempt will be made at a complete or analytical review of the voluminous and scattered literature on the strength of glass. For such treatments the reader is referred to several books and review articles in which the subject is considered at some length.[1] More detailed discussions of the literature of certain aspects of the subject also will be included in subsequent papers of this series.

### (1) Mechanical Condition of Surface

The nature and severity of any surface damage which may be present are quantitatively the most important factors affecting the strength of a glass specimen. Many investigators have demonstrated that the strength of truly undamaged bulk glass, with a fire-formed or acid-polished surface, is very high. Table I shows the results of several workers for various forms of glass.

In all cases shown in Table I the maximum strengths obtained were in excess of 100,000 lb. per sq. in. On the other hand, glass with a severely damaged surface containing obvious scratches, cracks, or bruises has a strength of 5,000 to 10,000 lb. per sq. in. As shown perhaps most clearly by Mueller and Mylchreest,† intermediate degrees of damage can lead to strength values anywhere between these two extremes.

Unless great care is exercised in the selection and handling of specimens for strength tests, they will normally show surface damage of widely varying degrees of severity. This is reflected in a very large statistical variation in the results, and the standard deviation of a set of strength values on supposedly identical specimens often is as high as 25%. Thus, strength

* Part II, "Effect of Various Abrasions and the Universal Fatigue Curve," will appear shortly in *The Journal of The American Ceramic Society*. Subsequent parts will be submitted.

[1] (*a*) J. E. Stanworth, Physical Properties of Glass, Chapter IV. Oxford University Press, London, 1950. 224 pp.; *Ceram. Abstr.*, 1950, October, p. 199*f*.

(*b*) G. W. Morey, Properties of Glass, 2d ed., Chapter XIII. American Chemical Society Monograph Series, No. 124, Reinhold Publishing Corp., New York, 1954. 591 pp.; *Ceram. Abstr.*, 1954, October, p. 180*h*.

(*c*) R. N. Haward, Strength of Plastics and Glass, Chapter III. Interscience Publishers, Inc., New York, 1949. 245 pp.; *Ceram. Abstr.*, 1951, February, p. 26*d*.

(*d*) E. Orowan, "Fracture and Strength of Solids [Metals]," *Repts. Progr. in Phys.*, 12, 185–232 (1948–1949).

(*e*) E. B. Shand, "Experimental Study of Fracture of Glass: I, The Fracture Process," *J. Am. Ceram. Soc.*, 37 [2] 52–60 (1954); "II, Experimental Data," *ibid.*, [12] 559–72.

† See footnote (*d*), Table I.

Table I. Strength of Undamaged Bulk Glass

| Specimen | Surface condition or test | Strength (lb./sq. in.) |
|---|---|---|
| Cane | Fresh-drawn pristine | 95,000–233,000[a] |
| | Commercial, redrawn* | 50,000–100,000[b] |
| | Acid etched and coated | 250,000[c] |
| Container glass | Pristine inner surface | 168,000[d] 110,000[e] |
| Flat glass | Microtest | 235,000[f] |

* Pulled down to smaller diameter in flame.

[a] R. M. Witucki, unpublished results.

[b] G. F. Stockdale, F. V. Tooley, and C. W. Ying, "Changes in Tensile Strength of Glass Caused by Water Immersion Treatment," *J. Am. Ceram. Soc.*, **34** [4] 116–21 (1951).

[c] See Shand, footnote 1(*e*).

[d] D. W. Mueller and G. D. Mylchreest, "Effect of Abrasion and Other Influences on Glass Surface Strength"; abstracted in *Glass Ind.*, 28 [10] 515 (1947).

[e] R. E. Mould, "Behavior of Glass Bottles Under Impact," *J. Am. Ceram. Soc.*, **35** [9] 230–35 (1952).

[f] H. E. Powell and F. W. Preston, "Microstrength of Glass," *ibid.*, 28 [6] 145–49 (1945).

measurements on specimens with an uncontrolled and unknown amount of surface damage are subject to high variability which can serve to mask the effects of other variables under study.

There are two possible methods of attempting to circumvent this difficulty. One can either attempt to use specimens which have pristine, undamaged surfaces or one can subject all specimens to some known, controllable form of damage. As a means of reducing variability, the first approach shows little promise. Past experiments have shown that, in general, the higher the strength, the greater is the variability. Thus, as the number and magnitude of the flaws present in the surface are reduced, the strength variation caused by those which remain becomes ever greater. There is no evidence that any experiments on bulk glass, as distinguished from fibers, have attained a degree of surface perfection great enough actually to lead to a decrease in strength variability.*

In contrast to the first, the second method is quite effective as a means of reducing specimen variability for strength tests on glass. If a uniform, reproducible form of surface damage is inflicted on the specimens before test, and if this damage is more severe than any previously present, the strength of all specimens can be reduced to approximately the same value and standard deviations as low as 5 to 10% of the mean value can be obtained.

Such a procedure has the additional advantages that different types of abrasions can be applied and their effects studied and that the results obtained may have more direct practical application since the strength ranges under study are then those normally encountered in commercial glassware.

### (2) Type and Duration of Load

It is well known that the measured strength of a glass specimen depends markedly on the duration or rate of application of the load used to test that specimen. This effect has been studied by several investigators.[2] For specimens which were tested wet, Baker and Preston found that the strengths for very short load durations (0.01 second) were about three times as great as those for a duration of one day.* Because of this large effect, any meaningful strength tests on glass must be conducted at a known or controlled rate of loading or with static loads of controlled duration. Since an understanding of static fatigue† or the gradual loss of strength under constant load is a necessary part of any complete understanding of the fracture process in glass, it is desirable that a systematic study also include a means of varying the rate of loading or load duration over a wide range.

### (3) Ambient Conditions During Test

Unfortunately little work has been done in which both the duration of the test and the environment of the specimen were subject to controlled systematic variation. The primary systematic studies of this nature which have been reported are those of Baker and Preston,[2(b)] Gurney and Pearson,[2(c)] and Vonnegut and Glathart,[3] who measured the strength and static fatigue of glass wet, in dry atmosphere and in vacuum, and in the last case as a function of temperature. The results show that both strength and static fatigue are greatly affected by the surrounding medium and by the temperature of test. Other investigators, notably Jones and Turner,[4] and Mengelkoch,[5] have also studied the effect of temperature, and Moorthy and Tooley[6] have reported on the effect of immersion in various liquids for tests at a single constant rate of loading.

In general, the investigations mentioned have shown that chemical attack plays an important role in the failure of a glass specimen under tensile stress. Many questions as to the specific nature of this attack remain unanswered, however.

### (4) Chemical Condition of Surface Before Test

Baker and Preston[2(b)] believed that their results were greatly influenced by the state of weathering of the surface flaws in their specimens. They believed that the strength and fatigue

* Some tests on glass fibers have produced small variability combined with very high strength values; see W. F. Thomas, "Strength of Glass Fibers," *Nature*, 181 [4614] 1006 (1958); *Ceram. Abstr.*, 1959, January, p. 8*c*, and R. E. Mould, "Cross-bending Tests of Glass Fibers and Limiting Strength of Glass," *Ceram. Abstr.*, 1959,

[2] (*a*) A. J. Holland and W. E. S. Turner, "Effect of Sustained Loading on Breaking Strength of Sheet Glass," *J. Soc. Glass Technol.*, 24 [101] 46–57T (1940); *Ceram. Abstr.*, 19 [8] 186 (1940).

(*b*) T. C. Baker and F. W. Preston, "Fatigue of Glass Under Static Loads," *J. Appl. Phys.*, 17 [3] 170–78 (1946); *Ceram. Abstr.*, 1946, August, p. 149.

(*c*) C. Gurney and S. Pearson, "Effect of Surrounding Atmosphere on Delayed Fracture of Glass," *Proc. Phys. Soc. (London)*, 62 [356B] 469–76 (1949); *Ceram. Abstr.*, 1949, November, p. 254*f*.

* Although delayed failure and static fatigue may play a role in some practical situations involving glass, the much greater magnitude of the effect of surface damage should never be overlooked. A very low breaking strength always implies severe surface damage or severe flaws regardless of the presence or absence of static fatigue. For example, an applied stress of 2000 lb. per sq. in. will not produce breakage, regardless of its duration, without the previous existence of surface damage in the form of cracks which are of sufficient size to be readily visible to the naked eye.

† Throughout this paper the terms "static fatigue" and "fatigue" refer only to the decrease of strength under constant load and not to alternating or cyclic loads such as are often implied by the terms "dynamic fatigue" or "fatigue" in other fields.

[3] B. Vonnegut and J. L. Glathart, "Effect of Temperature on Strength and Fatigue of Glass Rods," *J. Appl. Phys.*, 17 [12] 1082–85 (1946); *Ceram. Abstr.*, 1947, November, p. 222*a*.

[4] G. O. Jones and W. E. S. Turner, "Influence of Temperature on Mechanical Strength of Glass," *J. Soc. Glass Technol.*, 26 [113] 35–61T (1942); *Ceram. Abstr.*, 22 [1] 7 (1943).

[5] Karl Mengelkoch, "Temperature Dependence of Shearing Strength of Glass Rods," *Z. Physik*, 97, 46–63 (1935); *Ceram. Abstr.*, 17 [2] 66 (1938).

[6] V. K. Moorthy and F. V. Tooley, "Effect of Certain Organic Liquids on Strength of Glass," *J. Am. Ceram. Soc.*, 39 [6] 215–17

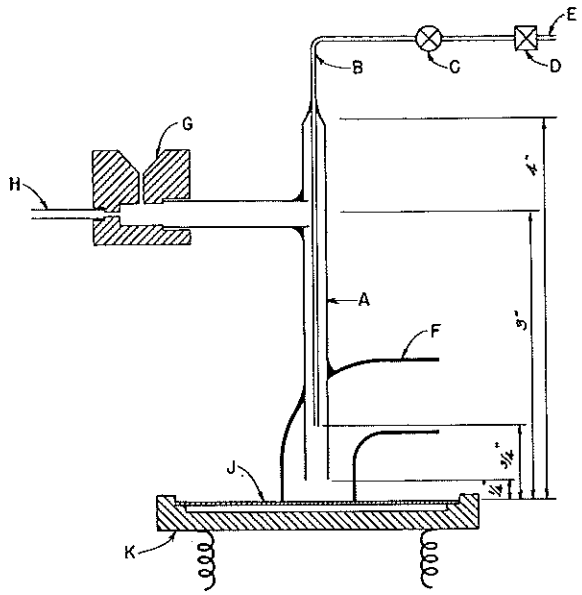


Fig. 1. Grit blaster for abrading glass specimens. (A) Nozzle, $^1/_4$ in. in outside diameter, $^1/_{16}$-in.-wall stainless steel tube; (B) blast tube, $^1/_{16}$ in. in outside diameter, 0.001-in. wall; (C) electric valve; (D) pressure regulator; (E) to prepurified nitrogen cylinder; (F) exhaust tube, $^1/_2$ in. in inside diameter; (G) grit funnel; (H) low-pressure nitrogen supply; (J) specimen; (K) spring-loaded specimen holder.

behavior of a freshly formed flaw might be markedly different from that of a flaw which had been exposed to the atmosphere for some time. To date no systematic work has been reported on this subject. Because of the important role played by chemical attack in connection with the fatigue of glass, and because of the complicated physical and chemical adsorption processes which can occur on a fresh or aged glass surface,[7] it seems almost certain that the history of exposure of the glass surface will influence the results of strength tests. Thus a complete systematic study of the strength of glass should include provision for chemical preconditioning of the specimens before test as well as provision for controlling the environment during test.

From a consideration of the experimental background described above, it is clear that an experimental program with the aim of producing a more complete understanding of the strength and static fatigue of glass should, as much as possible, provide for complete and systematic control of the physical and chemical environment of the specimen both before and during testing as well as of the nature and duration of the test itself.

## III. Description of Apparatus

The apparatus constructed for this study consists of three components: (1) a grit blaster for abrading the surfaces of the specimens, (2) test apparatus for the strength measurements, and (3) a controlled-condition chamber and its associated facilities in which the foregoing are mounted.

### (1) The Grit Blaster

Preliminary studies were carried out in which hand abrasion with emery cloth, diamond scratching, glass-to-glass contact, and grit blasting were compared as means for producing reproducible specimens for strength studies. As a result, it was decided that grit blasting, if carefully controlled, yielded both the smallest scatter of strength in any one sample and the least variation in strength from sample to sample when abraded at different times.

The grit blaster which was constructed as a result of these studies is illustrated schematically in Fig. 1. A tank of compressed nitrogen is used as the high-pressure source of the blast, the pressure being reduced to the desired value by a two-stage diaphragm-type pressure regulator. In operating the blaster the specimen is first placed in the spring-loaded holder (*K*) and a measured portion of grit is placed in the funnel (*G*). The electric valve (*C*), which is controlled by an electric timer, is then opened, permitting a blast of controlled duration to pass through the nozzle and against the surface of the specimen. The flow of gas creates a partial vacuum in the tube leading to the grit funnel, and nitrogen from the low-pressure supply carries the grit into the blast stream. Approximately 2 to 3 seconds is required for the grit to be exhausted from the funnel, and the blast is timed for 5 seconds. The additional blast after exhaustion of the grit serves to carry all grit and broken glass fragments away from the nozzle and specimen and into the exhaust tube.

The grit which has been used in this blaster is silicon carbide grain. All grit is sieved for several minutes through U. S. Standard sieves and the portion trapped between two predetermined sieves is used for blasting. After sieving, the grit is baked for several hours at 200°C. and then permitted to cool to room temperature before use to eliminate any moisture and to reduce any tendency for individual grains to stick to each other.

The nature of the damage produced and the effect of systematic variation of grit size and blast pressure on the strength obtained will be discussed in Part II of this series.

### (2) Test Apparatus

At various stages in this investigation three strength testers have been used. Preliminary measurements were carried out with a small impact tester. This was subsequently replaced with an electromagnetic loading device for applying pulse-type loads of short duration. For durations greater than about 1 minute, this tester was supplemented by a dead-weight tester which permitted the simultaneous testing of several specimens.

In all three testers the specimens, in the form of laths (standard microscope slides in most cases), were tested in cross bending with the abraded spot in the center of the span in the tension face. Thus in all the tests to be reported the fractures originated in the abraded area of the specimens.

In most cases a span length of $2^1/_2$ in. was used. Initially, three-point loading was used; i.e., the load was applied through a single central knife-edge. This was later replaced by four-point loading with double knife-edges ($^3/_8$-in. separation); the load was applied so that the abraded portion of the specimen would be in a region of uniform stress. Maximum stress in all cases was calculated from the appropriate formulas for beams in simple bending. A comparison of the three- and four-point loading methods on identical specimens showed that any difference in strength values produced by changing from one to the other was negligible for these centrally abraded specimens.

(*A*) *The Impact Tester:* The impact tester was a small pendulum-type device operated by solenoids. Repeated impacts of increasing severity were struck on the specimen until it broke. The impact was delivered through a small coil spring fixed to the face of the pendulum, thus lowering the natural frequency of the impact so that it was of long duration compared with the natural period of vibration of the specimens. The impact delivered took very closely the form of a half sine wave and could be considered as a very short duration pulse load.

Calibration was carried out by means of a specimen to which a wire resistance strain gauge was cemented. This

[7] B. J. Todd, "Outgassing of Glass," *J. Appl. Phys.*, 26 [10] 1238–43 (1955); *Ceram. Abstr.*, 1956, February, p. 32*i*.

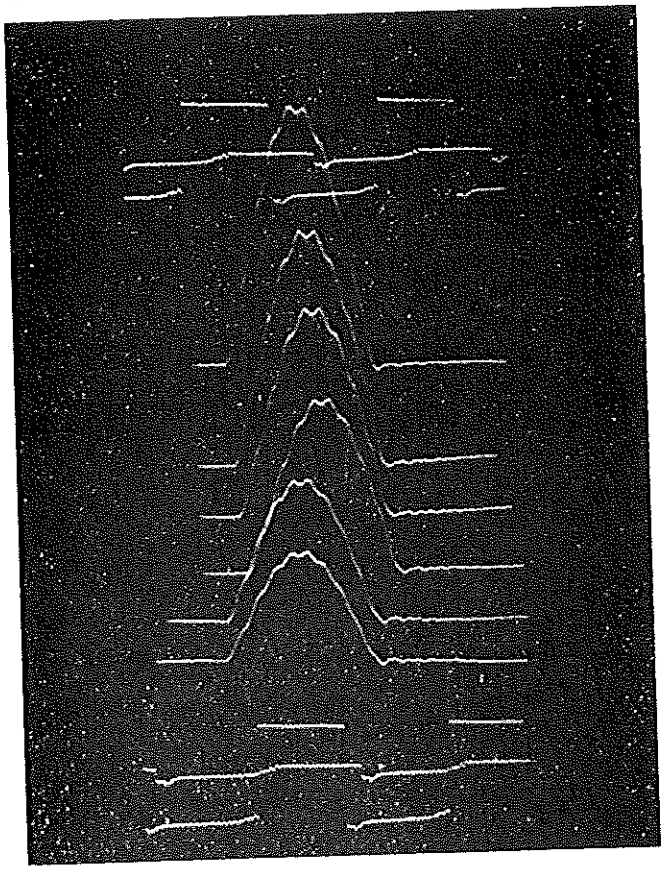

Fig. 2. Oscilloscope traces showing stress vs. time for specimen in impact tester for impacts of increasing severity. Base line displaced for subsequent traces. Sixty-cycle square waves at top and bottom are static load comparisons for stress calibration of impacts. Total duration of impact about 0.013 second.

specimen was loaded in the impacter and the unbalance signal of a Wheatstone bridge containing the strain gauge was amplified and presented on the face of a cathode-ray oscilloscope. Figure 2 is a multiple-exposure photograph of the face of the oscilloscope showing bending stress versus time for impacts of increasing severity in the tester. The signals at the top and bottom of the photograph are 60-cycle square waves which indicate the stress amplitude produced by hanging a known dead weight on the specimen across the same span used in the tester. The calibration was obtained by comparing the heights of the impact pulses with the stress produced by the dead-weight load.

A comparison with the 60-cycle trace shows that the total duration of the impact is about 0.013 second and the time for which the stress is greater than 90%* of the maximum value is about 0.0025 second. The small oscillations at the peak load are produced by resonant vibrations of the specimen and show that the excitation of such vibrations by the impact was negligible. Any attempt to shorten the duration of the impact, either by impacting through a stiffer spring or by omitting the spring, excited these vibrations so that their magnitude was comparable with that of the pulse itself.

(*B*) *The Electromagnetic Loader:* This tester consists essentially of an electromagnetic load coil and associated electronic apparatus for supplying accurately controlled currents to the coil. The mechanical portion of the tester is

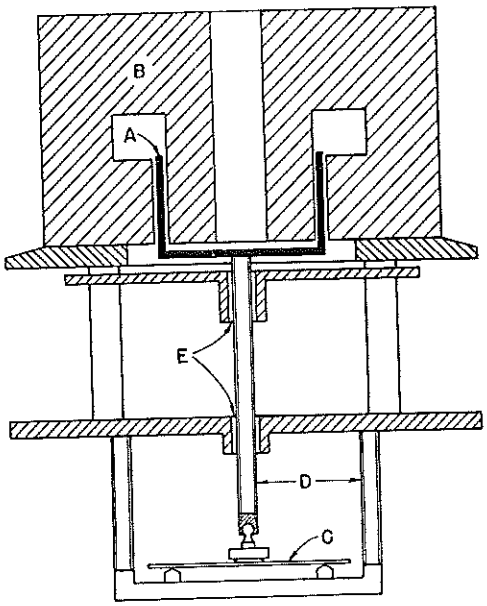


Fig. 3. Schematic drawing of mechanical portion of electromagnetic loader. (A) Coil on aluminum form, (B) loud-speaker permanent magnet, (C) specimen, (D) thin-walled stainless steel thrust and support tubes, (E) Teflon bearings.

pictured diagrammatically in Fig. 3. The coil (*A*) moves in the magnetic field of a loud-speaker permanent magnet (*B*) exerting a bending load on the specimen (*C*). The load exerted is equal to the small dead weight of the coil, connecting tube, and loading knife-edge, plus a force proportional to the current through the coil. Accurate control of this current assures an accurately determined load. Since the current can be changed, in effect, instantaneously, the only limitation on the speed of application or removal of a load is the mechanical inertia of the coil and the moving parts associated with it.

Current to the coil is supplied and controlled by electronic circuits which are indicated in a block diagram in Fig. 4. When the circuit is activated by pressing the start button, a square pulse is generated by the Eccles-Jordan circuit.[8] This pulse is differentiated to produce two voltage spikes. The first (negative spike) triggers the cathode-ray oscilloscope on which the operation of the tester is observed and the second (positive spike) triggers a phantastron pulse-generating circuit.[9] This circuit generates a highly linear saw-tooth pulse and a square pulse both of the same controllable duration. After appropriate shaping and amplification, these signals can be fed singly or in combination to the load coil.

With these circuits and other auxiliary switching facilities the following kinds of time variation can be incorporated in the current and therefore in the load applied to the specimen:

(1) *Constant Load:* A constant current (or load) can be switched on manually and will remain on until turned off. This is used in calibrating the tester. It also can be used for tests in which a constant stress is applied and a measurement made of the time until breakage occurs.

(2) *Pulse Load:* A constant load is applied and after a predetermined time is removed automatically. The shortest pulse time which the mechanical system will follow is about

* This sets an approximate upper limit to the effective duration of the load. A discussion of this test method will be presented in Part II of this series.

[8] J. D. Ryder, Electronic Fundamentals and Applications, p. 587. Prentice-Hall, Inc., New York, 1950. 806 pp.

[9] Britton Chance, *et al.*, Waveforms; Vol. 19, M.I.T. Radiation Laboratory Series, p. 195. McGraw-Hill Book Company, Inc., New York, 1949. 785 pp.

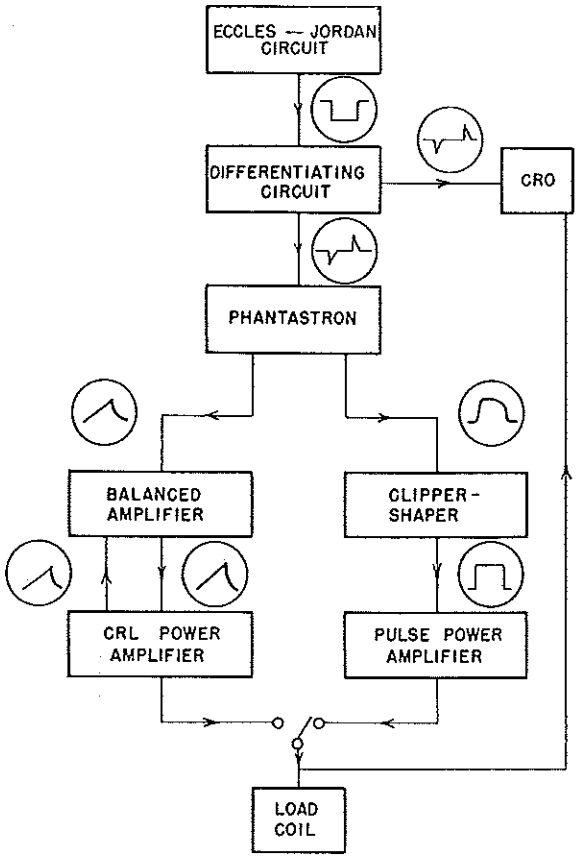


Fig. 4. Block diagram of electronic control circuits for electromagnetic tester. Arrows indicate path of signal.

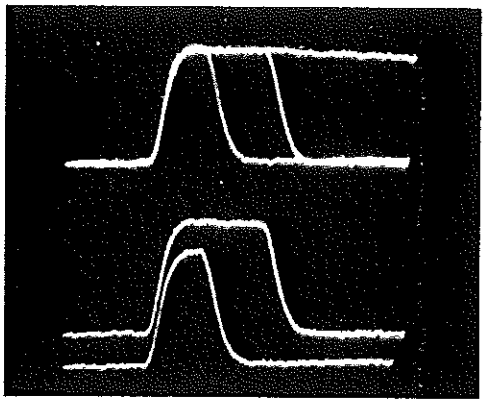

Fig. 5. Oscilloscope trace showing stress vs. time for specimen subject to pulse loads in electromagnetic loader (see text).

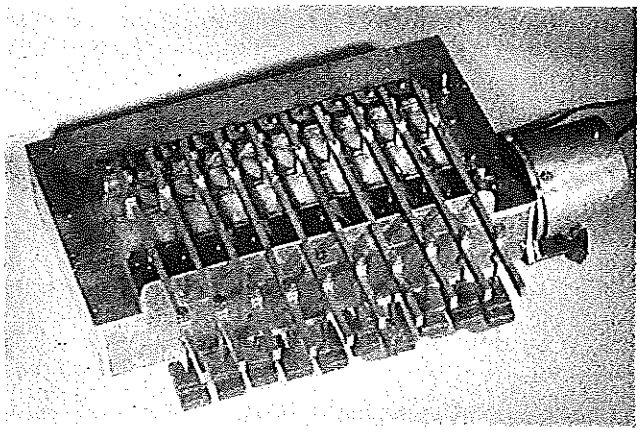

Fig. 6. Photograph of dead-weight tester showing ten individual loading stations with individual lever arms, weights, and dashpots.

0.0025 second, and the longest which can be applied is limited only by the patience of the operator. For most studies seven pre-set pulse times ranging from 0.0025 to 60 seconds were built into the control circuits. These pulse loads are used for step-wise loading tests in which pulses of increasing size are applied until the specimen breaks.

(3) *Constant Rate of Loading:* A load which increases at a constant rate until the specimen breaks can be applied automatically. The rate of application of the load can be varied over a wide range so that total loading times from about 0.01 second up to any desired value can be obtained.

(4) *Combination Loads:* Since the equipment contains parallel output channels, it is also possible to apply combinations of the foregoing loads. For example, either pulse or constantly increasing loads can be applied in addition to a constant load applied at some previous time. This feature was included to permit the study of the effect of prestressing on the strength of glass.

The tester was calibrated against a set of laboratory weights using a beam balance with the weights on one pan and the tester thrusting against the other. The calibration constant obtained in this way was reproducible to more than 1% accuracy. As with the impacter described, the dynamic mechanical responses of the tester and specimen were determined with specimens to which wire resistance strain gauges had been cemented.

The aluminum form for the loading coil moving in the magnetic field of the permanent magnet produced nearly critical damping for the system as originally constructed. The slight amount of remaining overshoot was removed by placing a condenser of proper size across the load coil, thus introducing some delay in the rise time of the loading current pulses.

Photographs of the stress versus time oscilloscope traces obtained for three pulse times after final adjustment of the equipment are shown in Fig. 5. In the upper photograph, traces for pulses of three durations (0.0025, 0.012, and 0.050 second) are superposed. In the lower photograph, traces for pulses of the two shortest times are shown with the base line shifted slightly to show the shape of each pulse more clearly. From the traces it can be seen that there is no overshoot and that pulses of all three durations have the same amplitude. The slight apparent falling off of the load for the 0.050-second pulse reflects the somewhat inadequate low-frequency response of the strain-gauge amplifier used and not a real decrease of the stress in the specimen.

For each pulse the effective duration of the pulse was taken as that time for which the load exceeded 90% of the maximum. Thus for the shortest pulse the total pulse duration was 0.009 second, but the effective duration was only 0.0025 second. As can be seen from Fig. 5, the time of application and release of the load was significant only for pulses of duration of about 0.01 second or less.

(*C*) *The Dead-Weight Tester:* For load durations greater than about 10 seconds, use of the electromagnetic loader was too time consuming, and a simple dead-weight tester was constructed for such tests. This tester is shown in Fig. 6. As can be seen from the photograph, the tester contains ten test stations each loaded independently by means of lead weights and pivoted loading arms. The loading arms are raised and lowered by a motor-driven cam so that the load duration can be controlled by an electric timer; each arm is equipped with an oil dashpot so that it will settle slowly if the specimen

under it breaks, thus preventing the breaking of one specimen from disturbing those remaining. Since this tester is used only for relatively long-time loads, the slow mechanical response produced by the dashpots has a negligible effect on the load duration.

### *(3) Controlled-Condition Facilities*

The controlled-condition chamber which was built for this study consists essentially of an airtight box in which an atmosphere of controlled temperature and composition can be produced and maintained. The grit blaster and all the testing apparatus described can be mounted inside the box and operated by use of accordion-sleeved Neoprene gloves and external electrical controls. In addition, internal access is provided to a vacuum furnace in which specimens can be vacuum baked at temperatures up to 550°C. and at pressures of the order of $10^{-6}$ mm. Hg.

Within the box the desired humidity is maintained by trays of drying agent or humidity-controlling saturated solutions. It is measured with a dew-point apparatus with which the dew point and therefore the relative humidity can be accurately determined. The internal temperature is maintained by a thermostatically controlled heater and the gas within the box is continuously circulated by a small fan driven through a hermetically sealed magnetic coupling.

## IV. Experimental Program and Summary

In the preceding section, apparatus and facilities have been described which were constructed to permit an extensive, systematic study of the factors that affect the strength of bulk glass. In their final form these facilities permitted a glass specimen to be subjected to a controlled, reproducible form of surface damage in a controlled environment. Subsequently the specimen could be stored or subjected to other treatments such as vacuum baking and then tested, all under controlled conditions and without exposure to normal room atmosphere. The test apparatus permitted the measurement of breaking stress for loads over a very wide range of durations so that for any given set of experimental conditions it was possible to obtain a complete static fatigue curve for the specimens.

With this apparatus the effect of the following variables on the strength and static fatigue of bulk glass has been studied: (1) The nature and severity of the abrasions present, (2) the degree of aging of the abrasions, i.e., the effect of various storage conditions and treatments from the formation of a fresh abrasion until the time of test, (3) the ambient medium during test, and (4) the temperature during test. Each of these topics will be the subject of a subsequent paper of this series.

Finally, the fact that no references to theories for the strength of glass have been made in this paper is not meant to imply that the approach used in this study has been entirely empirical. An attempt has been made throughout to relate the results obtained to existing theories where they seemed to have application and to understand the possible theoretical implications where no theory had as yet been formulated. As stated above, the aim of this study has been to work toward a complete and systematic understanding of those factors affecting the breakage of glass and especially of the physical-chemical surface reactions which play such a large role in the fracture process, and later papers will include discussions of the appropriate theoretical considerations.

#### Acknowledgments

The writers gratefully acknowledge the advice and encouragement provided by L. G. Ghering throughout the study reported in this and subsequent papers. Other members of the staff of Preston Laboratories also made valuable contributions. In particular Peter Kuttner and C. S. Kang assisted in the development of the electronic circuits for the electromagnetic tester. These circuits were based on a general design suggested by H. M. Dimmick of Dimmick Associates, Butler, Pennsylvania. The mechanical portions of the apparatus were built by G. F. Wiest, who made valuable contributions to their design.