FOREWORD

This work was performed by Stanford Research Institute under USAF Contract No. AF 33(657)-10600. The contract was initiated under Project No. 7350, "Refractory Inorganic Nonmetallic Materials," Task No. 735003, "Refractory Inorganic Nonmetallic Materials, Theory and Mechanical Phenomena." Work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio. Mr. G. R. Atkins was the project engineer.

This report covers work conducted from 15 January 1963 to 15 January 1964.

This program was under the specific direction of R. Sedlacek and the general direction of F. A. Halden

ABSTRACT

The tensile strength of a commercial, high alumina body was investigated by using hydraulically expanded cylindrical test specimens. Results were evaluated with respect to loading rate, surface finish, and microstructure. At various loading rates, uniform tensile strength data (coefficients of variation of less than 7.6 percent) were obtained in testing groups of specimens having the same fabrication history, while the differences in tensile strength between individual groups of specimens gave a measure of the over-all extent to which uncontrollable fabrication variables affect the tensile strength of alumina bodies.

This technical documentary report has been reviewed and is approved.

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I. INTRODUCTION

The increasing need of modern technology for new materials capable of mechanical performance under thermal and environmental conditions beyond the endurance of metals and alloys makes ceramics the most likely choice for replacement of conventional materials. Ceramics have a number of favorable properties for high temperature applications, e.g., strength, oxidation resistance, load-bearing capability, light weight, etc., but at the same time they have some far less attractive properties, which almost outweigh the favorable ones and constitute enormous obstacles to wider acceptance of these materials. Their brittleness and low tensile strength are the main drawbacks. Of these, brittleness is an inherent characteristic of ceramics at lower temperatures which eludes both precise definition and measurement, and the present state of technology offers little hope for improvement. On the other hand, the tensile strength of ceramics has been studied extensively, but with rather disappointing results. This property, however, can be measured, and must be accurately known if ceramics are to be used for structural purposes. In the past, tensile strength measurements produced a broad scatter of data, wholly inadequate for a realistic appraisal of the potential of these materials. Recently, it has gradually become evident that a large part of this data scatter is directly attributable to the faults of various test methods rather than to erratic performance of the test materials. These faults have various origins, but manifest themselves in the same way, namely, by the presence of parasitic stresses which are superimposed on the measured principal tensile stress, leading to premature failure of test specimens and erroneous results. To eliminate the most obvious sources of parasitic stresses, a new method of tensile testing has been conceived and reduced to practice at Stanford Research Institute. This method employs a cylindrical test specimen which is expanded by hydrostatic pressure acting radially against the inner wall, and is based on the characteristics of hydrostatic pressure, namely, the fact that the force is always normal to the specimen surface and is absolutely uniform at any point of contact. Experimental results previously obtained by this method[1,2] bear out the underlying theoretical principles, showing very uniform results and a high sensitivity to factors influencing the tensile strength of ceramics. This program was initiated in order to obtain sufficient test data over a range of test conditions and on a sufficient number of specimens to provide a real evaluation of the tensile strength of the test material and to indicate the true capabilities of the technique.

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[1] Sedlacek, R. and F. A. Halden, "Method of Tensile Testing of Brittle Materials," Rev. Sci. Instr., 33, pp 298-300, March 1962

[2] Sedlacek, R., "Measurement of the Effect of Parameters Influencing the Mechanical Properties of Ceramics," presented at the 16th Pacific Coast Regional Meeting of The American Ceramic Society, Oct. 23-25, 1963, Los Angeles

Manuscript released by author May 1964 for publication as an ASD Technical Documentary Report.

II. SUMMARY

The specific objectives of work performed under Contract No. AF 33(657)-10600 were: (1) to determine the true tensile strength of a high alumina body fabricated by a routine ceramic manufacturing process; (2) to establish the range of nonuniformity of tensile strength resulting from the effect of uncontrollable variables in an established manufacturing process; and (3) to investigate the dependence of tensile strength on loading rate. The following results were obtained.

At a loading rate of 3000 psi/sec, the maximum tensile strength of Wesgo AL-995 alumina bodies, ground to a surface finish of 20 to 35 microinches rms, was measured as 30,920 + 1175 psi. The modulus of elasticity was measured as $(57.3 \pm 2) \times 10^6$ psi and did not appear to be affected by loading rate.

Specimens were prepared in four batches to permit measurement of the effects on tensile strength of: (1) slight variations in chemical composition; (2) firing in different kilns; and (3) ground vs. "as-fired" surfaces. Specimens from each batch were measured as a function of loading rate from 70 psi/sec to 4500 psi/sec.

Each batch of specimens ground to specified tolerances had standard deviations in tensile strength less than 7.6%. The maximum deviation caused by investigated random manufacturing variations was 8.3%. Strength differences were consistent between batches under all testing conditions explored, indicating the reliability and sensitivity of this testing technique to minor property variations. Corresponding differences could not be found in grain size, purity, or porosity. Results indicate that measurement of tensile strength may be a far more sensitive and reliable measure of process variations than any other analytical technique.

Tensile strength was found to increase with increasing loading rate except at the highest rates studied. Subsequent calibrations of the testing equipment with high-speed recording instrumentation indicated that the recording equipment used at the time of this study may not have been able to follow the true stresses at the higher loading rates. Therefore, additional measurements, using the revised instrumentation, will be required to establish the true relationship of tensile strength and loading rate at the higher loading rates.

III. EXPERIMENTAL STUDIES

A. Material

Test specimens used in this work were a high-alumina commercial composition (AL-995) supplied by the Western Gold and Platinum Co., Belmont, California. They were fabricated in the shape of short cylinders having the following dimensions.

Outside diameter:	2.200 inch ± 0.001 inch
Inside diameter:	2.000 inch ± 0.001 inch
Length:	0.250 inch ± 0.001 inch

The specimens were fabricated in such a manner as to illustrate the extent to which uncontrollable variables inherent in a routine ceramic manufacturing process affect the tensile strength of the resulting bodies. The variables under study were: (1) batch-to-batch variation in chemical composition; and (2) differences in thermal history due to individual characteristics of various kilns. In addition to these variables, the effect of surface finish and dimensional uniformity on the tensile strength of finished pieces was also evaluated. All other fabrication steps were as uniform as a routine process would permit.

In order to assess the aforementioned variables, test specimens were divided into four groups and fabricated in the following manner.

Group A	originated in raw material batch No. A-449 and was fired in kiln No. 4
Group B	was made from the same batch (No. A-449), but was fired in kiln B
Group C	and Group D were prepared from raw material batch No. 467, and were fired simultaneously in kiln B.

All specimens of Groups A, B, and C were ground to final dimensions and a uniform surface finish. Specimens of Group D had only the end faces ground, the walls remaining in the "as-fired" condition.

In this arrangement the difference between average values of tensile strength of specimens of Groups A and B is attributable to variations in thermal history, whereas the variation of results between Groups B and C is primarily due to chemical composition. Specimens of Groups C and D were of identical composition and thermal history but varied in surface finish and dimensional uniformity. The difference in average values of tensile strength between these two groups indicates the effect

of surface finish. The different degrees of dimensional uniformity between Groups C and D were expected to result in a broader scatter of results in Group D.

A semiquantitative spectrographic analysis of the test materials was made by the American Spectrographic Laboratories in San Francisco, and the following figures represent oxides of the elements indicated.

	Batch A-449 (Groups A and B)	Batch 467 (Groups C and D)
Al	Principal constituent	
B	0.04%	0.05%
Si	1.75	2.0
Fe	0.12	0.12
Mg	0.8	1.0
Mu	0.001	0.001
Ga	0.04	0.05
Ti	0.015	0.01
Cu	0.007	0.005
Ca	0.06	0.06
Cr	0.001	0.001
Ba	0.003	0.002

The total of impurities amounts to 2.837% and 3.299% in batch A-449 and batch 467, respectively. Since Wesgo AL-995 is nominally a 99.5% alumina body, and has been found by other investigators to contain less than one percent of impurities, the analyses were repeated with emphasis on the silica and magnesia content, but identical results were obtained. Another set of materials was sent to a different laboratory for analysis. The results were not, however, available at this writing.

The thermal history can only be inferred from the known characteristics of the two kilns in which the test specimens were fired. Kiln B is a large furnace with a setting area of 30 x 90 inches. The total firing cycle is 30 to 32 hours. Kiln No. 4 has a setting area of 12 x 18 inches and a firing cycle of 24 to 28 hours. In both kilns the specimens were soaked at 1750°C for a period of three hours. The exact heating and

cooling curves are not known but kiln No. 4 is opened at a higher temperature than kiln B. Both kilns are gas-fired and the temperature is constantly monitored.

The dimensional tolerances of all ground specimens were well within the specifications, with wall thicknesses varying between 0.0997 inch and 0.1008 inch. The wall thickness of the "as-fired" specimens was between 0.102 inch and 0.107 inch. No significant out-of-roundness was found. All specimens tested had smooth edges, and a few specimens with chipped edges were discarded.

The grinding operation was carried out as follows. Approximately ten specimens were stacked and centerlessly ground to the final outside diameter dimension. Then each specimen was individually mounted in a special collet, faced and ground on the inside. The pebble tumbling treatment sometimes used for "deburring" of ground surfaces was not employed. The surface finish was measured with a Brush Instruments Model MS-1000 Surfindicator. The ground specimens (Groups A, B, and C) had a finish ranging from 20 to 35 microinches, while the finish of the "as-fired" specimens of Group D was 50 to 60 microinches. No differences could be detected between the batches of ground specimens.

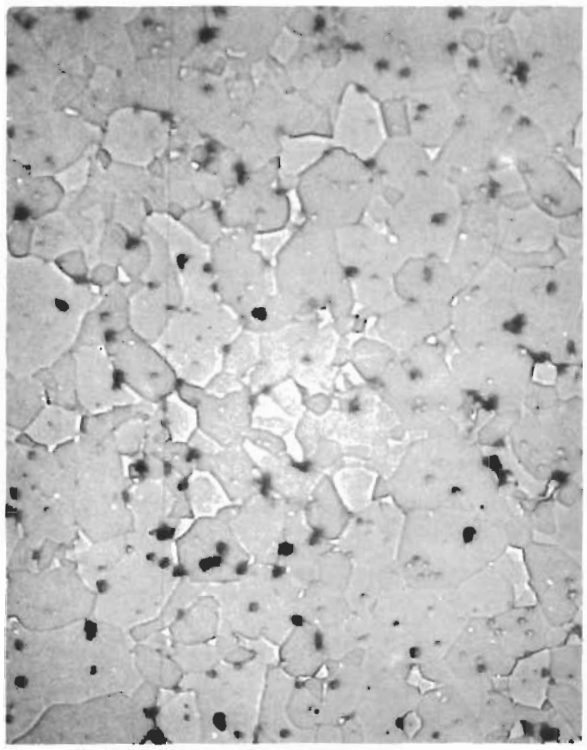
The microstructure of all four groups of specimens was very similar except for porosity, which was more pronounced in Group B than in the others. The average grain size did not vary from one group to another, the measured values being 23 microns in Group C, 25 microns in Group B, and 26 microns in Group A (Fig. 1). The pycnometric densities and weights of specimens of the individual groups are listed in Table 1. From these measurements it appears that the specimens are very uniform from batch to batch and that the only real difference which can be seen is the slightly higher porosity in Group B.

Table 1

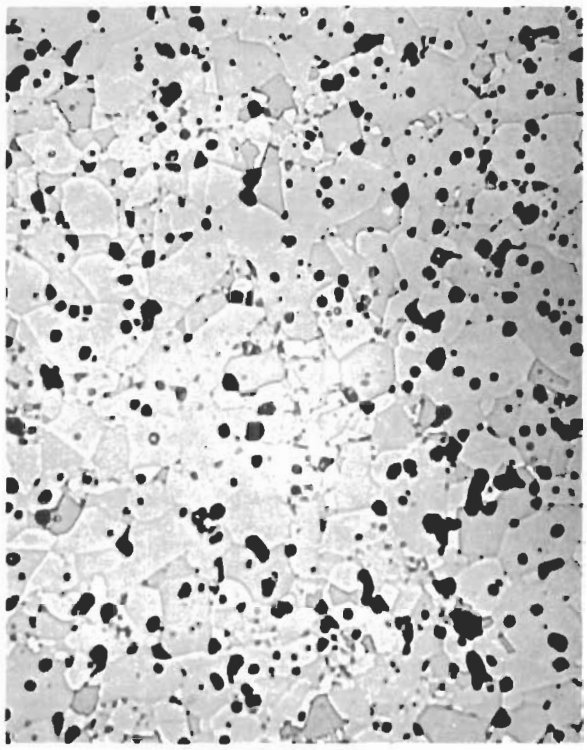
MICROSTRUCTURE, DENSITY, WEIGHT, AND SURFACE FINISH OF WESGO AL-995 SPECIMENS

Group	Density		Average Weight (g)	Grain Size (μ)	Surface Finish (microinches)
	(g/cc)	% of Theoretical*			
A	3.866	96.75	10.4363	26	20 - 35
B	3.846	96.25	10.3891	25	20 - 35
C	3.872	96.90	10.4279	23	20 - 35
D	3.866	96.75	10.7115	24	50 - 60

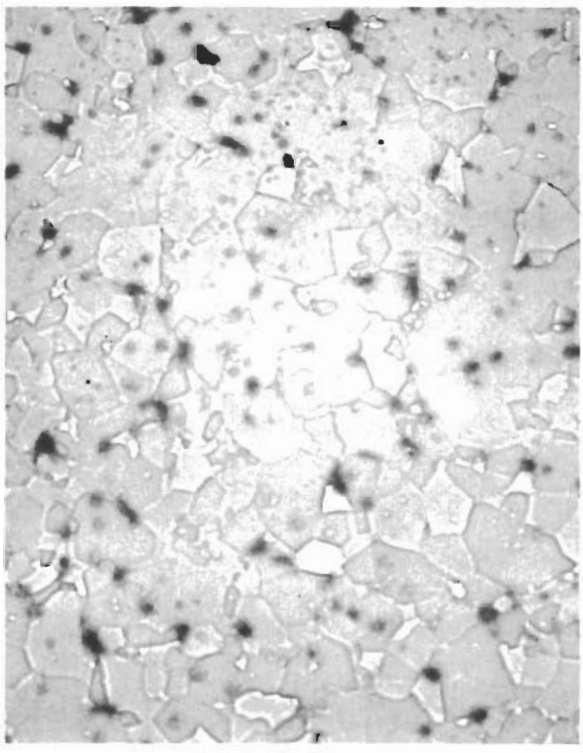
* Theoretical density--3.996 g/cc



(GROUP A)



(GROUP B)



(GROUP C)

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FIG. 1 PHOTOMICROGRAPHS OF ALUMINA (AI-995) SPECIMENS (X 200)

B. Apparatus

The main part of the apparatus used in this work was the specimen holder (Fig. 2) used in the original work, described elsewhere.[1] The specimen holder consists of two round steel plates containing machined cavities (one hemispherical, in the upper plate; and one conical, in the lower plate) having exactly the same inside diameter as that of the specimen. These cavities, facing each other, together with the test specimen inserted between them, form a vessel against whose wall hydrostatic pressure is applied radially from the inside through an elastomeric membrane. The conical cavity in the bottom plate opens to the outside and contains a steel plug equipped with a narrow canal through which the working fluid enters the pressure vessel. The membrane is squeezed between the two steel parts, forming a leak-proof seal. The outside of the canal is connected to the transducer manifold. The specimen holder is clamped together by a rigid steel frame which also came from the prototype apparatus. The rest of the equipment, however, was completely rebuilt and consisted of the following units.

1. Norwood Controls ElectroSyn system for sensing and monitoring hydrostatic pressure

2. Precision pressure gauge for standardizing the ElectroSyn system

3. Pressure generator consisting of a variable-speed transmission (Zeromax Type 40 JS 200R) driving a screw-actuated hydraulic ram of 30,000-psi capacity

4. Varian Type G10 strip chart recorder

5. Strain monitoring system consisting of SR-9 strain gauges (Type A-9-5 with 3-1/2-inch gauge length), Houston Instruments D. C. Amplifier and X-Y recorder

Although this arrangement proved in many respects vastly superior to the prototype, it had certain shortcomings which became evident only during actual testing and impaired the validity of some data. These shortcomings are discussed in Section V.

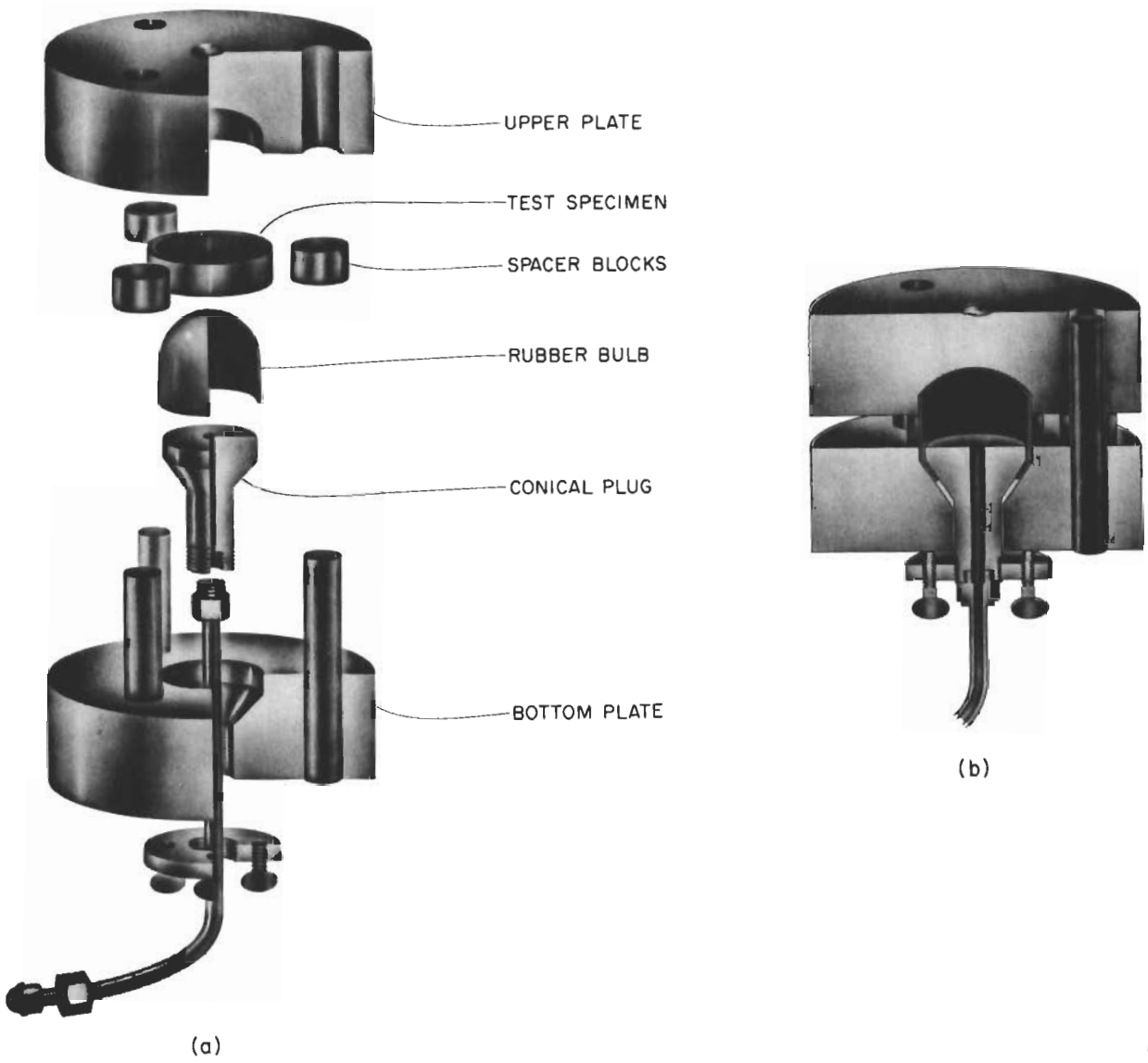

FIG. 2 TENSILE TEST SPECIMEN HOLDER
(a) Exploded view, (b) Assembled unit

C. Procedure

The testing procedure is simple and straightforward. With the rubber bulb firmly seated, and the upper plate of the specimen holder removed, the test specimen, whose height is accurately known, is placed in position, concentrically with the rubber bulb. Spacer blocks 1 to 2 mils higher than the test specimen, are placed around it, and the upper plate of the specimen holder is lowered into place. The entire assembly is clamped together so that, subsequently, the hydrostatic pressure does not alter the spacing of the specimen holder plates. The pressure generator is started, and hydrostatic pressure is recorded on a strip chart as a function of time. The most important factors are that the distance between holder plates remain constant during the experiment, and that the specimen in the assembled holder be free of any compressive constraint. The rubber bulb can be used repeatedly (its lifetime depends on the hydrostatic pressure applied), but after each experiment it must be cleaned of debris which could, subsequently, act as stress raisers.

IV. RESULTS

The tensile strength and elastic modulus data obtained for Wesgo AL-995 alumina are presented in Tables 2 through 7. The values of maximum tensile stress on the inside walls of test specimens were calculated by the formula

$$\sigma_{t\ max} = \frac{Pr_i^2}{r_o^2 - r_i^2}\left(1 + \frac{r_o^2}{r_i^2}\right)$$

where P = hydrostatic pressure at fracture (psi)

r_i = internal radius (inches)

r_o = external radius (inches).

For calculations of the elastic modulus E (Table 7), tensile stress values corresponding to measured strain were used. These stresses--whose locus is the outer wall of specimens to which strain gauges are attached--were calculated by the formula

$$\sigma_{t\ min} = \frac{2Pr_i^2}{r_o^2 - r_i^2} .$$

Standard deviations were calculated by the formula

$$s.d. = \sqrt{\frac{\Sigma d^2}{n}}$$

where d = deviation from average value of tensile strength

n = number of deviations.

Table 3

TENSILE STRENGTH OF WESGO AL-995 ALUMINA
AT THE LOADING RATE OF 1000 PSI/SEC

Group	Weight (g)	Ultimate Tensile Strength (psi)	Deviation (psi)
A	10.4201	26270	- 260
A	10.4243	25600	- 930
A	10.3830	26880	+ 350
A	10.4494	25090	- 1440
A	10.4433	28830	+ 2300
B	10.3830	24780	- 3100
B	10.3690	27280	- 600
B	10.3749	27780	- 100
B	10.3810	29910	+ 2030
B	10.3902	29640	+ 1760
C	10.4330	29190	+ 270
C	10.4062	28690	- 230
C	10.3842	28460	- 460
C	10.4433	27780	- 1140
C	10.4340	30250	+ 1330
C	10.3860	29130	+ 210
D	10.6396	27280	+ 1750
D	10.6411	25930	+ 400
D	10.7907	22560	- 2970
D	10.6250	24480	- 1050
D	10.6363	27420	+ 1890

Average:	Ultimate Tensile Strength (psi)	Standard Deviation (psi)
Group A	26530	± 1300 (4.90%)
Group B	27880	± 1837 (6.60%)
Group C	28920	± 758 (2.62%)
Group D	25530	± 1829 (7.16%)

Table 4

TENSILE STRENGTH OF WESGO AL-995 ALUMINA
AT THE LOADING RATE OF 3000 PSI/SEC

Group	Weight (g)	Ultimate Tensile Strength (psi)	Deviation (psi)
A	10.4205	28600	- 970
A	10.4024	29160	- 410
A	10.4064	28890	- 680
A	10.4321	28560	- 1010
A	10.4587	31080	+ 1510
A	10.4410	31720	+ 2150
A	10.4514	29530	- 40
A	10.4085	29000	- 570
B	10.3899	30060	+ 180
B	10.4383	30040	+ 160
B	10.3623	29470	- 410
B	10.3936	29640	- 240
B	10.3858	29800	- 80
B	10.3844	30040	+ 160
B	10.4062	28960	- 920
B	10.3880	28690	- 1190
B	10.3700	31760	+ 1880
B	10.3714	30380	+ 500
C	10.3974	32110	+ 1190
C	10.4152	29230	- 1690
C	10.4352	30310	- 610
C	10.4024	32160	+ 1240
C	10.4456	30070	- 850
C	10.4457	29100	- 1820
C	10.4615	32130	+ 1210
C	10.4241	31220	+ 300
C	10.4265	32500	+ 1580
C	10.3942	30380	- 540
D	10.6248	26520	- 3080
D	10.7617	31950	+ 2358
D	10.7022	27720	- 1880
D	10.6298	29200	- 400
D	10.7769	30310	+ 710
D	10.6662	30140	+ 540
D	10.7507	27950	- 1650
D	10.7722	33270	+ 3670
D	10.6621	28290	- 1310
D	10.6370	30710	+ 1110

Table 4 (Concluded)

Average:	Ultimate Tensile Strength (psi)	Standard Deviation (psi)
Group A	29,570	± 1110 (3.75%)
Group B	29,880	± 860 (2.87%)
Group C	30,920	± 1175 (3.80%)
Group D	29,600	± 1966 (6.65%)

Table 5

TENSILE STRENGTH OF WESGO AL-995 ALUMINA
AT THE LOADING RATE OF 4500 PSI/SEC

Group	Weight (g)	Ultimate Tensile Strength (psi)	Deviation (psi)
A	10.4334	22900	- 4620
A	10.4514	26900	- 620
A	10.4398	27850	+ 330
A	10.4396	28290	+ 770
A	10.4153	27780	+ 260
A	10.4314	29900	+ 2380
A	10.4723	29000	+ 1480
B	10.3430	26600	- 1870
B	10.3774	25960	- 2510
B	10.3922	29670	+ 1200
B	10.3971	29370	+ 900
B	10.3726	30440	+ 1970
B	10.3659	28420	- 50
B	10.4344	28960	+ 490
C	10.3970	28620	- 960
C	10.4564	29030	- 550
C	10.4230	30910	+ 1330
C	10.4042	31520	+ 1940
C	10.4012	29300	- 280
C	10.4050	30100	+ 520
C	10.4822	27610	- 1970
D	10.6607	27040	- 1960
D	10.6404	30510	+ 1510
D	10.7744	28220	- 780
D	10.7215	28098	- 910
D	10.6778	30880	+ 1880
D	10.8113	29230	+ 230

Average:	Ultimate Tensile Strength (psi)	Standard Deviation (psi)
Group A	27520	$\pm$ 2080 (7.55%)
Group B	28470	$\pm$ 1520 (5.35%)
Group C	29580	$\pm$ 1250 (4.25%)
Group D	29000	$\pm$ 1300 (4.48%)

Table 6

TENSILE STRENGTH OF WESGO AL-995 ALUMINA
AT THE LOADING RATE OF 4200 PSI/SEC

Group	Weight (g)	Ultimate Tensile Strength (psi)	Deviation (psi)
A	10.4202	29580	+ 560
A	10.4242	30180	+ 1160
A	10.4393	26270	- 2750
A	10.4318	27970	- 1050
A	10.4473	28730	- 290
A	10.4364	29950	+ 930
A	10.4642	30060	+ 1040
A	10.4145	29430	+ 410
B	10.3704	28480	+ 290
B	10.3892	28040	- 150
B	10.3758	30720	+ 2530
B	10.3515	27590	- 600
B	10.3835	26800	- 1290
B	10.4376	28510	+ 320
B	10.3640	29200	+ 1010
B	10.4041	26200	- 1990
C	10.4717	25980	- 2590
C	10.4385	28410	- 160
C	10.4532	27560	- 1010
C	10.4021	29430	+ 860
C	10.4725	25260	- 3310
C	10.4155	30880	+ 2310
C	10.3978	27340	- 1230
C	10.4485	30090	+ 1520
C	10.4115	32200	+ 3630
D	10.6900	22890	- 3410
D	10.7626	24090	- 2210
D	10.7113	23770	- 2530
D	10.6357	28540	+ 2240
D	10.7583	24880	- 1420
D	10.7869	28100	+ 1800
D	10.7143	27340	+ 1040
D	10.7519	31570	+ 5270
D	10.7212	25510	- 790

Average:	Ultimate Tensile Strength (psi)	Standard Deviation (psi)
Group A	29020	± 1250 (4.32%)
Group B	28190	± 1304 (4.60%)
Group C	28570	± 2155 (7.53%)
Group D	26300	± 2640 (10.05%)

Table 7

YOUNG'S MODULUS OF WESGO AL-995 ALUMINA

Group	Loading Rate (psi/sec)	E ($psi \times 10^{-6}$)
D	50	58.7
D	50	55.3
D	2000	53.2
D	2000	57.5
A	2000	59.2
A	2000	60.0
B	2000	55.5
B	2000	58.0
C	2000	55.5
D	4000	59.2
D	4000	58.6

V. CONCLUSIONS

The most important aspect of the data presented in the preceding tables is the low scatter of results within individual groups of specimens and the fact that this uniformity is accompanied by an equally pronounced sensitivity to factors influencing the tensile strength. It will be noted that the maximum variation of results within single groups of ground specimens is 7.55 percent (Table 5, Group A), and that in the majority of cases the standard deviations are less than 5 percent.

The numerical values of ultimate tensile strength obtained are of realistic magnitude, being higher than tensile strength values previously reported in the literature and approaching flexural values. Only in one instance[3] have somewhat higher tensile strengths been measured on the same material, but a direct comparison of results is made difficult by different gauge volumes of specimens used, and variations in loading rate.

The sensitivity of the method to factors influencing the tensile strength is best shown by the fact that with one exception the tensile strength values of the three groups of ground specimens follow in the same order of magnitude at all loading rates employed. This sequence is A <B <C (Table 8). The aforementioned exception occurred during the first series of measurements when specimens were tested at the loading rate of 4200 psi/sec (Table 6). It was found, after these measurements, that the force applied by the steel frame was insufficient to oppose the hydrostatic pressure inside the specimen holder. At pressures above 2300 psi, the hydrostatic pressure widened the spacing between the two plates of the specimen holder, allowing the rubber bulb to flow into the gap between the steel plates and the end faces of specimens. When this occurred, the normal stress pattern and loading rate were upset, and incorrect data were obtained. Once this difficulty was recognized it was easily remedied by increasing the load applied to the specimen holder, and it did not recur. For this reason the data obtained at a loading rate of 4200 psi/sec show a somewhat higher standard deviation than other sets of values and are considered to be less reliable.

Another indication of the sensitivity of SRI's tensile testing method can be seen in the effect of loading rate on tensile strength. Although the results are not conclusive, it can be seen that the tensile strength

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[3] Pears, C. D., et al., "Evaluation of Tensile Data for Brittle Materials Obtained with Gas Bearing Facility," Technical Documentary Report No. ASD-TDR-63-245, under USAF Contract No. AF 33(657)-7685.

Table 8

AVERAGE VALUES OF TENSILE STRENGTH OF WESGO AL-995 ALUMINA SPECIMENS OF COMPARABLE SURFACE FINISH

Loading Rate (psi/sec)	Average Tensile Strength (psi)	Standard Deviation (psi)	Group
70	24210	± 497 (2.05%)	A
	25340	± 965 (3.36%)	B
	26050	± 1220 (4.67%)	C
1000	26530	± 1300 (4.90%)	A
	27880	± 1837 (6.60%)	B
	28920	± 758 (2.62%)	C
3000	29570	± 1110 (3.75%)	A
	29880	± 860 (2.87%)	B
	30920	± 1175 (3.80%)	C
4500	27520	± 2080 (7.55%)	A
	28470	± 1520 (5.35%)	B
	29580	± 1250 (4.25%)	C

increases with increasing loading rate--at least within the range of dependable performance of the apparatus (Tables 2, 3, and 4). The fact that tensile strength values fall off again at the highest loading rate employed (4500 psi/sec, Table 5) poses a question. While it may be assumed that the tensile strength may reach a maximum, corresponding to a certain loading rate, beyond which the strength value remains constant, or even decreases, due perhaps to the effect of a different failure mechanism, it is difficult to believe that the relatively low loading rate of 4500 psi/sec represents this limit. It is more likely that the reason for this discrepancy lies in some malfunction of the equipment. The most likely source of faulty performance is the ElectroSyn pressure-monitoring system. This unit is essentially an electro-mechanical, null-balance system employing a geared servo-motor of limited response (4-6 seconds from 0 to 5000 psi). Theoretically, this response should be sufficiently fast to monitor pressures at loading rates up to 10,000 psi/sec. However, at the fastest setting the Zeromax

transmission produced very strong vibrations, shaking the entire apparatus. It is conceivable that these vibrations could jam the gears of the servo-motor, causing it to slow down, in which case the signal to the recorder would be lagging, and the recorded maximum pressure would fall short of the actual value.

In order to check this possibility, a new pressure sensing system (Wiancko), whose signal is fed directly into a Visicorder, was installed. This system has a dynamic response of 400 cps. With both systems (ElectroSyn and Wiancko) manifolded in line, the pressure was raised repeatedly at different loading rates to levels corresponding approximately to 30,000 psi of tensile stress, and the performance of the two pressure measuring systems was compared. It was found that the performance was the same up to a loading rate of approximately 10,000 psi/sec. Above this rate, as is shown in Table 9, the tensile stress values recorded by the two units began to diverge rapidly.

Table 9

STANDARDIZATION OF THE PRESSURE MONITORING SYSTEM

Loading Rate (psi/sec)	Tensile Stress Wiancko (psi)	Tensile Stress ElectroSyn (psi)	Lag of ElectroSyn (%)
10,900	34,010	32,860	3.4
14,200	41,090	33,970	17.4
16,000	44,800	33,560	25.0
18,000	48,530	33,120	31.6
19,300	52,060	33,080	36.5

Unfortunately, it was not possible to derive from these values a correction factor applicable to the data of Table 5 for the following reasons. The loading rate is determined from the slope of the recorded pressure-time curve. If the ElectroSyn signal lagged behind the actual pressure, then not only the recorded pressure but also the loading rate is incorrect. Furthermore, the effect of vibrations on the performance of the ElectroSyn cannot be evaluated because these vibrations have been eliminated since the latest modifications.

Test results also cast some light on the validity of a number of factors which are conventionally considered in correlating tensile strength with microstructure. Although the limited scope of this study

did not permit an extensive analysis, certain aspects are pronounced enough to merit mentioning. It can be seen that significant differences in tensile strength between individual groups of specimens are accompanied by differences in microstructure which are too small for microscopic detection. For instance, the tensile strength of the three groups of ground specimens varies by as much as 8.3 percent (Table 3, difference between A and C), whereas the average grain size remains within the range of normal data scatter. It also can be seen that microstructural evidence may lead to wrong conclusions as to the tensile strength. Specimens of Group B were stronger than those of Group A, although the former were considerably more porous, and the opposite would have been expected.

Surface finish in the conventional sense was not, strictly speaking, a studied variable in this work, because only two extremes were employed. No systematic difference of finish could be found between individual groups of ground specimens to account for the differences in tensile strength. It is not possible to make a simple comparison of tensile behavior between the ground specimens and those in the "as-fired" state. It can be seen that the "as-fired" specimens (Group D) are much weaker than those of Group C, although both have the same composition, thermal history, and microstructure. The only difference between these two groups of specimens therefore lies in the condition of the surface. It must be realized that this difference is more one of kind than of degree. It is not likely that a mere difference of 30 microinches in surface finish is responsible for an 11.7 percent difference in tensile strength (between C and D in Table 3). The surface of the "as-fired" specimens can conceivably contain discontinuities, too small to be detected by a profilometer, whose effect is much more severe than that of various degrees of waviness of a continuous surface. Less energy is required to propagate an existing crack than if the crack has to be created first. This may explain why specimens of Group D are weaker than those of Group C, notwithstanding the greater wall thickness of the former. On the other hand, this assumption does not explain the erratic response of the "as-fired" specimens to loading rate, and more work will be required before this phenomenon can be better understood. In general, it appears that the effect of the "as-fired" surface exceeds the effects of all other variables considered in this work, and that a certain amount of surface preparation is essential if meaningful results are to be obtained.

The tensile strength data obtained in this work give an illustration of the extent of variation in mechanical properties that can be expected to be found in ceramic materials fabricated commercially by a routine process containing several rather poorly controlled variables. It can be

seen that the tensile properties of these materials are considerably more uniform than has been thought heretofore. The largest variation of tensile strength found is 8.3 percent (between A and C in Table 3), which is less than the spread of results obtained by conventional testing methods. This variation represents the combined effects of all variables present, and the scope of this work did not allow room for analysis of individual factors.

Most of the values of Young's Modulus (Table 7) are somewhat higher than those generally reported for this and similar materials (55×10^6 psi). No conclusions can presently be drawn as to correlation of these data with tensile strength values of individual groups of specimens, nor does it appear that there is any systematic relationship between this property and the loading rate.

VI. RECOMMENDATIONS FOR FUTURE WORK

It is believed that the continued use and improvement of SRI's method of tensile testing can lead to major gains in better understanding of the complex field of mechanical properties of refractory materials. Two types of investigation should be undertaken.

1. Initial studies should be concentrated on commercially available materials fabricated under existing technological criteria and should subject these materials to a thorough investigation of their tensile properties. This study must not be limited to tensile testing under constant stress rates, but should include static loading to failure at various stress levels, static fatigue, cyclic loading at various frequencies and amplitudes, evaluation of size effect, consideration of environmental factors, etc. Such a study performed on a statistically meaningful scale will undoubtedly shed much light on existing theories of the brittle state, and should produce results of practical importance to the designer.

2. Conventional ceramic fabrication processes are the result of a long pragmatic development, and as such are seldom supported by adequate theoretical understanding. This makes it nearly impossible to modify the characteristics of these materials so as to make them suitable for a new application. However, ceramics have a number of properties that make them a natural choice for structural use, and sooner or later they will have to be adapted to new applications. To this end an extensive study should be undertaken in which the accuracy and sensitivity of SRI's tensile testing method would be used in determining--directly in terms of tensile strength--the manner in which changes in individual manufacturing steps influence this property. Such a study, carried out on a simple system, e.g., high purity Al_2O_3, would in the end, yield a composite of quantitative data necessary for realization of improved and dependable ceramic products having predictable characteristics.