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DETERMINING AND ANALYZING THE STRENGTH AND IMPACT RESISTANCE OF HIGH MODULUS GLASS

by

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EAST HARTFORD, CONNECTICUT 06108

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Report K911105-3

Determining and Analyzing the Strength and Impact of High-Modulus Glass

SUMMARY

An error was noticed recently in the computer program used to reduce the laboratory sonic measurements to tabulated values of Young's modulus of the bulk samples of experimental glasses. Correction of this error gave revised values for the last fifty experimental glasses prepared in this laboratory. This corrected data, when examined as input material for the calculation of Young's modulus of bulk glasses from composition by the C. J. Phillips procedure (Ref. 1), resulted in new values for the contribution per mol of several oxides. The new value for the zinc oxide molal factor is especially significant since it is slightly greater than the factor for beryllia for the types of glasses melted in the UARL research program. This discovery provides a new tool in the search for nontoxic, i.e. without beryllia, high modulus glass fibers particularly when coupled with last quarter's measurements that showed zinc oxide contributes significantly to increased impact strength.

The report also includes new glass compositions prepared in this period and the latest impact strength values measured.

INTRODUCTION

This report is the third quarterly report for the UARL-NASA Headquarters Contract NASW-2209, Determining and Analyzing the Strength and Impact Resistance of High Modulus Glass. This contract is the successor to the prior UARL contracts NASW-1301, Investigation of the Kinetics of Crystallization of Molten Binary and Ternary Oxide Systems and NASW-2013, Investigation of the Kinetics of Crystallization of Several High Temperature Glass Systems. The time period covered by the present report is August 1, 1971 through October 31, 1971.

For the earlier NASA contracts, UARL studied the rate of crystallization of several unusual molten oxide systems not normally used for glass production. The two most interesting of these systems were the cordierite-rare earth oxide and the invert analog-rare earth oxide fields with both of these systems at times including beryl additions. In each of these systems a number of high modulus, high strength glass compositions were found and some of these compositions could be fiberized by the usual platinum-rhodium bushing drawing

technique. The fibers thus produced were used to form glass fiber-epoxy resin composites and these were characterized as fully as possible. The strength and impact characteristics of these high modulus glasses in bulk form were not investigated however.

The present contract has as its purpose a more systematic investigation of the properties of bulk samples of those high modulus glasses previously developed and an attempt to correlate such properties with composition and microstructure. New compositions will also be prepared and studied both in bulk and as fibers if they show promising viscosity-temperature relationships. These investigations may contribute in a small way to the need for more information about glass in massive form that the National Advisory Board of the National Research Council has indicated (Refs. 2,3) to be a prerequisite for the successful use of glass as an engineering material.

NEW GLASS COMPOSITIONS

The new glass compositions prepared in this period are shown in Table I. Using the revised program for calculating moduli from sonic test results discussed in detail in a later section of this report, it was possible to accurately predict in advance the value for Young's modulus for a number of these glasses. It should be possible, therefore, in the future to move more rapidly toward our goal of a nonberyllia containing high modulus glass fiber. It will be noted that only two of the glasses prepared in this period contain beryllia in line with our recent emphasis on nontoxic glasses.

REVISED PROGRAM FOR CALCULATION OF YOUNG'S MODULUS OF BULK GLASS SAMPLES

In our summary report (Ref. 4) a computer program was written for the determination of the elastic modulus of a material in the form of a cylinder using the formulae developed by Pickett (Ref. 5).

The determination of the elastic modulus simply requires the evaluation of the following expression:

$$E = (C)\ (\text{weight})\ (\text{resonant frequency})^2.$$

The constant C is evaluated according to the expression

$$C = 0.0041632\ (L/D)^3\ T$$

with the parameter T evaluated for the diameter and length of the specimen according to

Table I

New Glass Compositions
(in mol %)

Actual Ingredient	481	482	483	484	485	486
SiO_2	55	65	65	65	62	58
Al_2O_3	17	12	17	7	12	12
MgO	17	12	7	17	12	10
Li_2O	--	--	--	--	3	--
CaO	--	--	--	--	--	10
Y_2O_3	10	10	10	10	10	10
CoO (Co_2O_3)	1.0	1.0	1.0	1.0	1.0	--

	487	488	498	490	491	492
SiO_2	59	49	47	51	47	47
Al_2O_3	10	10	22	17	17	17
MgO	10	10	17	17	17	17
Li_2O	--	--	3	3	3	3
CaO	10	10	--	--	--	--
ZnO	--	--	--	--	--	6
Y_2O_3	10	10	3	6	10	10
CoO (Co_2O_3)	1.0	1.0	--	--	--	--
BeO	--	10	--	--	--	--
Cu_2O	--	--	6	6	6	--

	493	494	495	496	497	498
SiO_2	45	65	57	36	40	56
Al_2O_3	17	--	--	--	--	7.75
MgO	17	12	12	12	14	--
Li_2O	3	--	--	9	12	2
CaO	--	12	12	12	18	22.25
ZnO	6	--	8	--	--	--
Y_2O_3	10	10	10	10	10	10
TiO_2	--	--	--	4	4	--
CoO (Co_2O_3)	--	1.0	1.0	2	2	2
BeO	--	--	--	15	--	--
Cu_2O	2	--	--	--	--	--

Table I (Cont'd)

	499	500	501	502	503
SiO_2	40	30	30	45	39
Al_2O_3	2.66	--	--	--	--
MgO	18	20	20	12	15
Li_2O	2	3	2	2	2
CaO	16	15	12	12	15
Ce_2O_3	--	--	--	2	--
B_2O_3	--	8	8	--	--
ZrO_2	4	3.66	4.5	2	6
Y_2O_3	10	12	12	10	10
TiO_2	7	8	11	10	12
CoO (Co_2O_3)	0.33	0.33	0.5	1	1
ThO_2	--	--	--	4	--

$$(A) \qquad T = 1.0 + 81.79(D/2L)^2 - (1314(D/2L)^4)/(1 + 81.09(D/2L)^2) - 125(D/2L)^4.$$

For this calculation, Poisson's ratio has been taken as 1/6, and the factors T and C are those which yield an approximate solution to the differential equations for transverse vibrations as determined by Goens.

In addition to the straightforward calculation, a feature of the program used is a subroutine which can be used to sort the output data in terms of any desired parameter, such as sample diameter. With this feature, checks for systematic variations in calculated modulus values with a chosen parameter can easily be made. The program itself is written in FORTRAN IV for use with a time-shared computing system. The Research Laboratories provides this capability by either an in-house PDP-6 (Digital Equipment Corp.) computer, or by subscription to the General Electric time-shared computing system.

Unfortunately, when this program was stored in the computer, the first exponent in Eq. (A) was changed from 2 to 3. This fact gave us a series of wrong moduli values reported in our last two reports (Refs. 6,7). The program in the computer has now been corrected as shown below and the corrected results for Young's moduli of recent experimental glasses are given in the next section.

Corrected Computer Program

```
CCCC PRØGRAM TØ CALCULATE GLASS BULK MØDULUS BY THE FØRMULATIØN OF PICKETT
CCC INPUT DATA GLASS IDENTIFICATIØN, WEIGHT IN GRAMS, DIAMETER
CCC IN INCHES, LENGTH IN INCHES, RESØNANT FREQUENCY IN KILØCYCLES
CCC
CCC
  DIMENSIØN DIA(50),WT(50),RF(50), E(50)
  DIMENSIØN INDEX(50)
  REAL LE
  ALPHA TITLE
  DIMENSIØN TITLE(10), LE(50)
  READ("PICKVAL",81)NTØT,TITLE
  81 FØRMAT(5X,13,10A4)
  READ("PICKVAL",85)(WT(N),DIA(N),LE(N),RF(N), N=2,NTØT)
  85 FØRMAT(5X,4F10.4)
  NN = NTØT -1
  DØ 50 N=2,NTØT
  M = N-1
  INDEX(M) = M; WT(M)=WT(N); DIA(M)=DIA(N);LE(M)=LE(N);RF(M)
 & = RF(N)
  50 CØNTINUE
  DØ 55 N = 1,NN
  A = DIA(N)/(2.*LE(N))
  T=1. + 81.79*A**2 - 131.4*A**4/(1. + 81.09*A**2) -
 & 125.*A**4
  C = 0.004163/DIA(N) * (LE(N)/DIA(N))**3 * T
  E(N) = C * (WT(N)/453.59) * RF(N)**2
```

```
  55 CØNTINUE
  CALL SØRT( DIA, NN, INDEX )
  PRINT 123, TITLE
  123 FØRMAT(1H , 10X,10A4)
  PRINT," "
  PRINT," J  L    DIA     LENGTH     WEIGHT      FREQ
 &      MØDULUS"
  DØ 501 J=1,NN
  L = INDEX(J)
  PRINT 135,J,L,DIA(J),LE(L),WT(L),RF(L),E(L)
  501 CØNTINUE
  135 FØRMAT(1H ,2I3,3F10.4,2F14.4)
  STØP; END
  SUBRØUTINE SØRT( A, NPØINTS,INDEX)
CCC INDEX IS FILLED WITH INDEXING INTEGERS FRØM 1 TØ NPØINTS
CCC ARRAY IS BRØUGHT IN AS A SINGLY SUBSCRIPTED ARRAY
  DIMENSIØN A(50),INDEX(50)
  M = NPØINTS
  1 M = M/2
    1F ( M .EQ. 0 ) RETURN
    K = NPØINTS - M
    J = 1
    2I = J
    3IM = I + M
    IF[A(I)-A(IM)]5,5,4
CCC SWITCH VALUES AND ARRANGE INDEX ARRAY
  4 SAV = A(I); NSAV = INDEX(I)
    A(I) = A(IM); INDEX(I) = INDEX(IM)
    A(IM) = SAV; INDEX(IM) = NSAV
    I = I-M
    IF (I. GE. 1) GØ TØ 3
    5J = J + I
    IF (J-K)2,2,1
    END
```

REVISED VALUES FOR YOUNG'S MODULUS OF BULK GLASS SAMPLES

Using the corrected program, new values for Young's modulus were determined for all glasses previously calculated with the erroneous program and these values are listed in Table II. The magnitude of the change made may be seen from the fact that the old value for UARL 468 glass was 15.48×10^6 psi while the corrected value is 17.01×10^6 psi. Since the erroneous equation has been erased from the computer's memory bank, no further trouble is anticipated in the programmed calculation of Young's from the raw laboratory data.

Table II

Corrected Values for Young's Modulus Measured on Circular Rods Formed Directly from Melt

Glass No.	Density gms/cm^3	Density lbs/in^3	Young's Modulus millions psi	Specific Modulus 10^7 inches	Glass No.	Density gms/cm^3	Density lbs/in^3	Young's Modulus millions psi	Specific Modulus 10^7 inches
433	3.6325	0.1308	19.12	14.65	458	3.2094	0.1158	15.23	13.15
434	3.5304	0.1273	19.43	15.35	459	3.4538	0.1242	17.34	13.95
435	3.4605	0.1247	20.36	16.33	460	3.3785	0.1215	16.83	13.84
436	3.4461	0.1246	19.90	16.05	461	3.0354	0.1092	14.80	13.54
437	3.5067	0.1265	19.41	15.35	461[1]	3.3823	0.1218	26.0	21.3
438	3.2348	0.1165	18.28	15.68	462	3.3294	0.1198	16.53	13.82
439	3.3510	0.1207	20.03	16.63	463	3.4296	0.1235	17.85	14.45
440	3.3426	0.1203	19.72	16.37	464	3.0700	0.1105	16.12	14.60
441	3.2739	0.1181	19.52	16.52	465	3.3184	0.1193	16.66	13.95
442	3.5959	0.1297	20.02	15.45	466	3.0731	0.1108	15.95	14.42
443	3.6695	0.1326	20.10	15.17	467	3.4302	0.1238	16.82	13.55
444	3.5011	0.1263	19.33	15.35	468	3.4426	0.1242	17.01	13.70
445	3.4488	0.1245	17.63	14.16	469	3.3773	0.1219	16.33	13.39
446	3.5049	0.1263	20.01	15.85	470	3.3020	0.1193	16.75	14.05
447	3.2975	0.1188	18.23	15.35	471	3.1743	0.1145	17.90	15.63
448	3.5173	0.1268	17.08	13.45	472	3.2183	0.1162	18.20	15.67
449	3.3944	0.1223	18.08	14.80	473	too high a forming temperature			
450	3.3598	0.1212	17.78	14.65	474	too high a forming temperature			
451	3.5527	0.1280			475	too high a forming temperature			
452	3.6114	0.1302			**476	2.9125	0.1048	18.44	17.57
453	3.6837	0.1327			477	3.2277	0.1166	18.62	15.95
454	3.6142	0.1303	18.93	14.53	478	3.2992	0.1189	18.46	15.52
455	3.2860	0.1186	15.96	13.46	479	3.0768	0.1108	16.69	16.55
456	3.2099	0.1158	15.02	13.00	480	3.3397	0.1204	18.12	15.54
457	3.1765	0.1144	15.93	13.89	481	3.2284	0.1167	18.30	15.70

[1]crystallized

**UARL 476 is Bastian, U.S. Patent 2,978,431 - max. ingredients

Table II (Cont'd)

Glass No.	Density gms/cm^3	Density lbs/in^3	Young's Modulus millions psi	Specific Modulus 10^7 inches
482	3.1492	0.1137	16.83	14.81
483	3.1451	0.1135	16.69	14.69
484	3.1560	0.1138	15.98	14.05
485	3.2110	0.1157	16.83	14.55
486	3.1853	0.1145	16.10	14.07
487	3.2004	0.1155	16.08	13.93
488	3.3235	0.1200	17.87	14.90
489	3.0710	0.1108	16.72	15.12
490	3.2900	0.1187	17.78	14.98
491	3.4625	0.1248	18.68	14.95
492	3.3920	0.1223	18.55	15.15
493	3.4562	0.1247	18.64	15.28
494	3.2678	0.1180	16.30	13.82
495	3.5578	0.1287	17.24	13.42
496	3.3972	0.1226	19.18	15.65
497	3.3829	0.1222	18.63	15.27
498	3.2500	0.1175	16.22	13.80
499	3.6049	0.1303	19.50	14.95
500	3.5944	0.1297	18.97	14.63
501	3.6174	0.1307	19.02	14.58
502	3.8924	0.1403	19.02	13.57
503	3.6528	0.1318	19.55	14.85
134A	3.0983	0.1116	16.86	15.12
152	4.3834	0.1580	15.27	
160	3.2452	0.1170	17.09	14.53
345B	3.3594	0.1216	20.66	17.00
*425B	2.7561	0.0995	18.81	18.90

*UARL 425 is National Bur. of Standards Glass 389 (Ref. 4)

NEW FACTORS AND CALCULATIONS FOR THE PREDICTION OF YOUNG'S MODULUS

The corrected values for Young's modulus from Table II together with the earlier values for UARL glasses 1 through 424 which required no correction since they were calculated by hand and not by computer were used to form the input data for an extension of the C. J. Phillips (Ref. 1) method of predicting Young's modulus from the composition. This method is based on the procedure of expressing each oxide in mol percent and multiplying it by a modulus factor peculiar to that oxide. Originally, Phillips derived coefficients only for certain oxides likely to be present in the usual glasses; namely SiO_2, Na_2O, K_2O, Li_2O, B_2O_3, Al_2O_3, CaO, MgO, PbO, BaO, ZnO and BeO. This series of calculations extends the list of coefficients available to include those for Y_2O_3, ZrO_2, La_2O_3, Ta_2O_5, TiO_2, CoO, Ce_2O_3 and makes a small correction in the value for MgO as well as a very large correction for ZnO. Of course, the glasses prepared at UARL have been primarily either cordierite base-rare earth oxide glasses or invert analogs with major rare-earth additions so that the calculations are not necessarily universally applicable to the more common commercial glasses but would be expected to hold for all glasses used to produce glass fibers since these normally contain very little alkali.

As stated above, the numerical value for the predicted Young's modulus of a given glass is the sum of the terms

$$C_1 P_1 + C_2 P_2 + \ldots + C_n P_n$$

where C_1, C_2, ... C_n are molal coefficients and P_1, P_2, ... P_n are the molar percentages of the corresponding oxides. The agreement obtained as well as the details of the calculations are shown for 58 of the UARL experimental glasses. The calculations start with simple ternary oxide systems such as silica-alumina-magnesia and build through quarternary systems to systems involving nine or ten oxides. The results of the new determinations of all the molal coefficients are given in Table III. It will be noted that beryllia makes a contribution of nineteen kilobars/mol to Young's modulus and that ceria, lanthana, zinc oxide, zirconia, and yttria all make a contribution at least as large. The result for zinc oxide for the UARL glasses is especially surprising since the original work of Phillips showed a contribution of only 1.75 kilobars/mol rising with R_2O increase while this work shows a value of 20.0 kilobars/mol. Phillips (Ref. 1) original calculations for zinc were based primarily on barium silicate glasses while the present investigation is concerned largely with silica-magnesia-alumina-yttria-zinc oxide systems and it may be possible that in such systems tightens the divalent oxygen ions in exactly the same manner as beryllia (Ref. 8). The contribution of 20 kilobars/mol of zinc oxide therefore appears much more likely than the value of 1.75 kilobars/mol. The details of these calculations are shown in Appendix I.

Table III

Summary of All Experimentally Determined
Molar Modulus Coefficients

Oxide	Contribution Per Mol (kilobars)	Oxide	Contribution Per Mol (kilobars)
SiO_2	7.3	ZnO	20.0
Al_2O_3	12.1	ZrO_2	23.8
CaO	11.45	MgO	13.64
Li_2O	7.0	Ce_2O_3	19.6
B_2O_3	7.2	Y_2O_3	28.6
TiO_2	15.0	La_2O_3	18.6
BeO	19.0	Ta_2O_5	19.4
		CoO	11.0

RECENT GUIDE LINES FOR THE DEVELOPMENT OF NEW NONTOXIC GLASS FIBERS

The directions in which UARL is moving toward the goal of a high modulus high strength nontoxic glass fiber are best summarized by reference to Table IV. This table, unfortunately, does not express fully the significance of the discovery that zinc oxide can make a major contribution to Young's modulus because of the newness of this finding. It does not reflect either that we have found recently that zirconia additions cause a marked alteration in the viscosity-temperature curves of highly fluid glasses. Finally, the fiberization characteristics of those glasses contained in Table IV are in many cases still under investigation. With these exceptions, however, it would appear that improved glasses similar to UARL-237, 402, and 449 may provide the desired composition.

COMPARATIVE IMPACT RESISTANCE OF SEVERAL UARL BULK GLASSES

Research studies on the effect of composition on impact resistance of bulk glasses have continued in this period with the results shown in Table V. For each glass, eight samples were prepared by aspirating the molten glass into a fused silica tube by means of a hypodermic syringe. The round glass rods were then cut to standard length for Charpy specimens and regarded as unnotched Charpy specimens. They were then impacted in a Wiederman-Baldwin Tester, an impact tester of Bell Laboratory design, using a one foot pound hammer, a thirteen inch pendulum, and a two foot drop. As all who have used this type of test know, the results are somewhat variable so that the average test data listed in Table V is designated as the "best logical average". A more precise meaning may be attached to this term by examining the data of Table VI which shows just how much variation can occur in two typical sets of test data. For UARL 323 glass the best logical average is obtained by striking out the two extreme values found while for UARL 417 glass the true average is employed although the data varies from 0.8159 to 1.0570 ft lbs/in^2.

CONCLUSIONS

1. The data of this report indicate that a possible new approach to obtaining a high modulus high strength nontoxic glass fiber is to substitute zinc oxide for beryllia since it has now been shown that zinc oxide with a contribution of 20 kilobars/mol should be at least as effective as beryllia which makes a contribution of 19 kilobars/mol in producing such a glass.

2. The introduction of zine oxide into a glass normally increases the fluidity of such glasses so that additions of materials such as zirconia will be necessary to achieve satisfactory working range glasses.

Table IV

A Further Guide to the Development of a Nontoxic Fiberizable Composition Having an Absolute Modulus Greater than 15.6 x 10^6 psi, Specific Modulus 14.6 x 10^7 in or Better and Readily Fiberizable. Includes N.B.S. 389 (UARL 425) for Comparison Although this Glass Cannot Be Readily Fiberized and Does Contain Beryllia

Glass No.	Mol Sum	Density gms/cm^3	Modulus 10^6 psi	Spec. Mod. 10^7 in.	SiO_2	Al_2O_3	MgO	Li_2O	CaO	ZnO	ZrO_2	Y_2O_3	BeO	CoO	B_2O_3	TiO_2	Cu_2O	Fe_2O_3	Re_2O_3	Ce_2O_3	Can be Fiberized
231		3.43	18.05	14.6	40	14	36					10									
235		3.33	17.4	14.4	50	10	30					10									X
236			17.8	14.3	43	15	30					10									
237		3.33	18.3	15.2	45	15	30					10									X
266	61.5	3.187	16.7	14.5	25	15	15	15	15	15											
270	70.13	3.53	20.3	15.9	25	8	15	15	15	15		7									
304		3.62	19.65	15.2	35	15	30			10		10									
306		3.67	18.9	14.3	35	15	30			5		10		5							
321		3.63	18.7	14.2	40	15	30					15									X
329		3.03	20.7	18.9	22.2	11.11	22.22	11.11		11.11	11.11	11.11									
333		3.71	18.9	14.1	39	12	25			12		12									
337		3.94	20.9	14.9	30	15	30			12.5		12.5									
357	91.6	3.40	17.6	14.4	39	12	24	6		6		3							10		
360	76.9	3.52	18.5	14.6	39	12	24	6		6		10		3							
361	79.2	3.50	18.5	14.8	39	12	24	6		6		10						3			
362	77.0	3.50	18.0	14.3	39	12	24	6		6		10					3				
363	76.3	3.57	19.26	14.9	39	12	24	6				10			6		3				
383	64.9	3.14	22.75	20.02	24	3	16	12	12	8	12				10		3				
391A	78.5	3.31	17.38	14.6	17	6	16	12	12	8		12			17						
402	83.1	3.31	17.77	14.85	25	8	20	5	9			14			14	3	2				X
403	86.2	3.37	17.17	14.05	25	8	20	5	6			14			14	3	2	3			X
449	77.0	3.39	18.08	14.8	25		20	6	15	4		12			13	3	2				X 15.82
450	79.7	3.36	17.78	14.65	38		15	10	15	10		12									
454	80.5	3.61	18.93	14.53	38	6	20	6	9	4		12				3	2				
464	64.1	3.07	16.12	14.6	25		15	15	15	10		5			15						X 14.83
466	60.5	3.07	15.95	14.4	25		15	15	15	15		2.5			12.5						
471	70.8	3.17	17.9	15.63	25	8	15	15	10	15		7			5						
480	68.7	3.34	18.12	15.54	55		4		12			10	16	1							readily?
481	80.6	3.23	18.30	15.70	55	17	17					10		1							
491	84.8	3.46	18.68	14.95	47	17	17	3				10					6				
492	83.4	3.39	18.55	15.15	47	17	17	3		6		10									
494	73.96	3.27	16.30	13.8	65		12		12			10		1							readily?
502	90.12	3.89	19.02	13.6	45		12	2	12		2	10		1		10			$4ThO_2$	2	readily?
425B	49.3	2.74	18.81	18.99	42.9	7	25.6						24.6								
425A	49.5	2.74	19.51	19.7	42.9	7	25.6						24.6								
461 cryst.	63.4	3.38	26.0	21.3	25		13	13	13	13	10				13						

Table V

Latest Impact Resistance Test Results

Glass No. UARL	Impact Value ft-lbs/in.^{2} (best logical average)	Glass No. UARL	Impact Value ft-lbs/in.^{2} (best logical average)
454	1.103	459	1.017
347	1.188	304	1.098
419	1.008	383	0.887
336	1.0013	350	0.902
344	0.954	425	0.867
447	0.947	417	0.926
237	0.976	323	0.775
331	1.116	"E"	0.711

Tests were carried out using a one foot pound hammer on the Wiedemann-Baldwin tester, an impact tester of the Bell Laboratory design with a thirteen inch pendulum and a two foot drop. The specimens are all round rod asperated samples and are used as unnotched Charpy specimens

Table VI

Impact Resistance Test in Detail for
Two Typical Bulk Glasses

Glass No.	Impact Value ft/lbs	Diameter inches	Area Square Inches	Corrected Impact Value ft-lbs/in^2
417	0.065	0.311	0.0760	0.8557
	0.060	0.301	0.0712	0.8432
	0.060	0.306	0.0735	0.8159
	0.085	0.320	0.0804	1.0570
	0.07175	0.316	0.0784	0.9149
	0.07575	0.312	0.0764	0.9909
	0.07175	0.308	0.0745	0.9631
	0.06970	0.306	0.0735	0.9478
			Logical Average	0.926
323	0.054	0.296	0.0688	0.7848
	0.055	0.307	0.0740	0.7431
	0.08945	0.307	0.0740	~~1.2085~~
	0.04175	0.312	0.0764	~~0.5461~~
	0.05125	0.303	0.0716	0.7155
	0.0640	0.304	0.0726	0.8818
	0.05935	0.318	0.0794	0.7473
	0.0575	0.307	0.0740	0.7768
			Logical Average	0.775

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APPENDIX I

Latest Modulus Calculations Based on Method of C. J. Phillips

1. Using UARL glass #69 to determine MgO contribution

	Mol %	Kilobars/Mol	Contribution
SiO_2	57.3	7.3	418
Al_2O_3	14.6	12.1	177
MgO	28.0	X	28X
			595+28X

Actual exp. value for UARL 69 = 14.16×10^6 psi = 977 kilobars

$$\therefore x = \frac{977-595}{28} = 13.64 \text{ kilobars/mol for MgO}$$

2. Checking experimental data for glasses 1, 4, 14 using this value for MgO

SiO_2	52.3	7.3	382
Al_2O_3	18.7	12.1	226
MgO	29.2	13.64	398
			1006 kilobars calc.

Actual average exp. value for glasses 1, 4, 14 = 14.96×10^6 psi measured on ground rods cut from a fully annealed specimen. To reconcile the differences between the "as cast" (aspirated rods) usually used and the fully annealed rods used here, we find experimentally that we must subtract 0.3×10^6 psi.

$\therefore$ corrected exp. value for UARL glasses 1, 4, 14 = 14.66×10^6 psi = 1008 kilobars exp.

3. Checking experimental data for UARL glass #68 using this value for MgO

SiO_2	53.4	7.3	390
Al_2O_3	18.3	12.1	221
MgO	28.8	13.64	393
			1004 kilobars calc.

Using the values for the aspirated rods and those as well for the ground samples with the 0.3×10^6 million psi subtraction correction the average experimental value = 14.61×10^6 psi = 1008 kilobars exp.

APPENDIX I (Cont'd)

4. Using the experimental data for UARL glass 114 to derive an yttria factor

	Mol %	Kilobars/Mol	Contribution
SiO_2	51.7	7.3	377
Al_2O_3	22.5	12.1	272
MgO	15.8	13.64	216
Y_2O_3	10.0	X	$\frac{10X}{865+10X}$

But experimentally UARL 114 has a value = 16.69×10^6 psi = 1151 kilobars exp.

$$\therefore Y_2O_3 \text{ factor} = \frac{1151-865}{10} = \frac{286}{10} = 28.6 \text{ kilobars/mol}$$

5. Using the experimental data for UARL glass 321 to check the yttria factor just found

SiO_2	40	7.3	292
Al_2O_3	15	12.1	182
MgO	30	13.64	409
Y_2O_3	15	28.6	429
			1312 kilobars calc.

Actual exp. glass for UARL glass 321A = 18.68×10^6 psi = 1288 kilobars exp.

6. Checking the yttria factor derived by use of data for glass 129

SiO_2	50	7.3	365
Al_2O_3	13.33	12.1	161
MgO	26.67	13.64	365
Y_2O_3	10	28.6	286
			1177 kilobars calc.

But experimentally UARL glass 129 = 16.57×10^6 psi - 1143 kilobars exp.

7. Checking the yttria factor derived against experimental data for UARL 127

SiO_2	60	7.3	438
Al_2O_3	10	12.1	121
MgO	20	13.64	273
Y_2O_3	10	28.6	286
			1118 kilobars cals.

But actual exp. value for UARL 127 = 16.13×10^6 psi = 1112 kilobars exp.

APPENDIX I (Cont'd)

8. Checking yttria factor derived against experimental data for UARL glass #70

	Mol %	Kilobars/Mol	Contribution
SiO_2	55.3	7.3	404
Al_2O_3	12.6	12.1	152
MgO	29.3	13.64	400
Y_2O_3	2.83	28.6	81
			1037 kilobars calc.

But experimentally the value for UARL glass 70 = 15.23 x 10^6 psi on fully annealed ground bars
= 14.93 x 10^6 corrected to correspond to aspirated bars
= 1030 kilobars exp.

9. Checking the yttria factor by use of data for UARL glass #64

SiO_2	54.6	7.3	399
Al_2O_3	15.5	12.1	188
MgO	28.8	13.64	393
Y_2O_3	1.39	28.6	40
			1020 kilobars calc.

But experimentally UARL #64 on annealed, ground bars has a value = 15.18 x 10^6 psi correcting this to obtain a comparative aspirated rod value = 14.88 x 10^6 psi
= 1026 kilobars exp.

10. Checking the yttria fact by use of data for UARL glass #231

SiO_2	40	7.3	292
Al_2O_3	14	12.1	169
MgO	36	13.64	491
Y_2O_3	10	28.6	286
			1238 kilobars calc.

But experimentally UARL glass #231 has a value = 18.65 x 10^6 psi = 1245 kilobars exp.

11. Checking yttria factor by use of data for UARL glass #235

SiO_2	50	7.3	365
Al_2O_3	10	12.1	121
MgO	30	13.64	409
Y_2O_3	10	28.6	286
			1181 kilobars calc.

But experimentally #235 has an experimental value = 17.38 x 10^6 psi = 1200 kilobars exp.

APPENDIX I (Cont'd)

12. Checking yttria factor by use of data for glass 237A

	Mol %	Kilobars/Mol	Contribution
SiO_2	45	7.3	329
Al_2O_3	15	12.1	182
MgO	30	13.64	409
Y_2O_3	10	28.6	286
			1206 kilobars calc.

But experimentally UARL 237A has a value = 17.91 x 10^6 psi = 1235 kilobars exp.

13. Checking yttria factor by use of data for glass #151

SiO_2	49.4	7.3	351
Al_2O_3	6.1	12.1	74
MgO	36.5	13.64	498
Y_2O_3	8.0	28.6	229
			1152 kilobars calc.

But experimentally UARL glass 151 has a value = 16.9 x 10^6 psi = 1166 kilobars

14. Checking the yttria factor by use of data for glass #159

SiO_2	57.4	7.3	419
Al_2O_3	6.6	12.1	80
MgO	28.0	13.64	382
Y_2O_3	8.0	28.6	229
			1110 kilobars calc.

But experimentally UARL glass 159 has a value = 16.2 x 10^6 psi = 1118 kilobars

15. Computing the lanthana factor by use of data for UARL #263

SiO_2	67.3	7.3	491
Al_2O_3	12.1	12.1	146
MgO	3.9	13.64	53
La_2O_3	16.8	X	16.8X
			690+16.8X

But experimentally glass 263 = 14.49 x 10^6 psi = 1000 kilobars

$$\therefore La_2O_3 \text{ factor} = \frac{1000-690}{16.8} = \frac{310}{16.8} = 18.5 \text{ kilobars/mol}$$

APPENDIX I (Cont'd)

16. Checking lanthana factor by use of data for UARL #136

	Mol %	Kilobars/Mol	Contribution
SiO_2	53.31	7.3	389
Al_2O_3	15.56	12.1	188
MgO	28.89	13.64	394
La_2O_3	2.00	18.5	37
			1008 kilobars calc.

But experimental glass 136 has a laboratory modulus = 14.4×10^6 psi = 993 kilobars exp.

17. Checking lanthana factor by use of data for UARL #138

SiO_2	47.31	7.3	345
Al_2O_3	15.56	12.1	188
MgO	28.89	13.64	384
La_2O_3	8.00	18.5	148
			1065 kilobars calc.

But experimentally glass 138 = 15.3×10^6 psi = 1055 kilobars exp.

18. Checking the lanthana factor by use of the data for UARL #135

SiO_2	54.31	7.3	396
Al_2O_3	15.56	12.1	188
MgO	28.89	13.64	384
La_2O_3	1.00	18.5	19
			987 kilobars calc.

But experimentally UARL glass 135 = 14.3×10^6 psi = 986 kilobars exp.

19. Checking the lanthana factor by use of experimental data for UARL #152

SiO_2	49.4	7.3	361
Al_2O_3	6.1	12.1	74
MgO	36.5	13.64	488
La_2O_3	8.0	18.5	148
			1071 kilobars calc.

But experimentally UARL glass 152 has a value = 15.27×10^6 psi = 1053 kilobars exp.

APPENDIX I (Cont'd)

20. Checking the lanthana factor by use of experimental data for UARL #319

	Mol %	Kilobars/Mol	Contribution
SiO_2	45	7.3	328
Al_2O_3	15	12.1	182
MgO	30	13.64	409
La_2O_3	10	18.5	185
			1104 kilobars calc.

But experimentally glasses UARL 319 & 319A have a value = 16.21×10^6 psi = 1118 kilobars exp.

21. Checking the lanthana factor by use of experimental data for UARL #63

SiO_2	54.6	7.3	399
Al_2O_3	15.6	12.1	189
MgO	28.9	13.64	394
La_2O_3	0.95	18.5	18
			1000 kilobars calc.

But experimentally glass 63 has a value of 14.7×10^6 on fully annealed and ground bars and has a comparable value of 14.41×10^6 psi on aspirated rods = 994 kilobars exp.

22. Using the data for UARL experimental glass #117 we find factor for ceria

SiO_2	51.67	7.3	377
Al_2O_3	10	12.1	121
MgO	18.33	13.64	250
Ce_2O_3	20	X	20X
			748+20X kilobars calc.

But actually the exp. value for UARL glass 117 = 16.54×10^6 psi on fully annealed ground rods or = 16.24×10^6 psi after applying the correction necessary for comparison with aspirated rods, i.e. = 1120 kilobars

$$\therefore \text{ Ceria factor} = \frac{1120-748}{20} = \frac{372}{20} = 19.6 \text{ kilomars/mole}$$

APPENDIX I (Cont'd)

23. Using the data for UARL experimental glass #72 to check ceria factor found

	Mol %	Kilobars/Mol	Contribution
SiO_2	56.9	7.3	415
Al_2O_3	15.1	12.1	183
MgO	25.4	13.64	346
Ce_2O_3	2.60	19.6	51
			995 kilobars calc.

But experimentally UARL glass 72 has a value of 15.15×10^6 psi on fully annealed ground rods and arriving at corrected factor necessary for comparison with aspirated rods = 14.85×10^6. We have also measured aspirated rods of #72 with a result = 14.03×10^6 psi. Average of these values = 14.44×10^6 psi = 996 kilobars exp.

24. Using the data for UARL experimental glass #62 to check the ceria factor found

SiO_2	54.6	7.3	399
Al_2O_3	15.2	12.1	184
MgO	29.2	13.64	398
Ce_2O_3	1.0	19.6	20
			1001 kilobars calc.

But experimentally UARL glass 62 = 14.18×10^6 psi = 977 kilobars exp.

25. Using the experimental data for Owens-Corning OCX-2124 (Ref. 2) to obtain beryllia factor

SiO_2	70.0	7.3	511
Al_2O_3	12.5	12.1	151
BeO	17.4	X	17.4X
			662+17.4X

But Owens-Corning obtained experimentally 14.4×10^6 psi = 993 kilobars for this formulation

$$\therefore \text{ BeO factor} = \frac{993-662}{17.4} = 19.0 \text{ kilobars/mol}$$

26. Using the data for UARL glass 318 to verify beryllia factor just found

SiO_2	45	7.3	329
Al_2O_3	15	12.1	182
MgO	30	13.64	409
BeO	10	19.0	190
			1110 kilobars calc.

But experimentally UARL 318 has value = 15.97×10^6 psi = 1101 kilobars exp.

APPENDIX I (Cont'd)

27. Using the data for UARL #66 to calculate the zirconia factor

	Mol %	Kilobars/Mol	Contribution
SiO_2	53.7	7.3	392
Al_2O_3	15.3	12.1	185
MgO	28.3	13.64	386
ZrO_2	2.56	X	2.56X
			963+2.56X

But experimentally UARL 66 has a value = 15.14×10^6 psi on fully annealed ground rods and correcting this to obtain comparative value for an unannealed aspirated rod = 14.84×10^6 psi = 1024 kilobars

$$\therefore ZrO_2 \text{ factor} = \frac{1024-963}{2.56} = 23.8 \text{ kilobars/mol}$$

28. Using the experimental data for UARL 320 to verify the zirconia factor

SiO_2	45	7.3	329
Al_2O_3	15	12.1	182
MgO	30	13.64	409
ZrO_2	10	23.8	238
			1158 kilobars calc.

But experimentally UARL 320B3 = 16.58×10^6 psi = 1143 kilobars exp.

29. Using the data for UARL glass 155 to derive the value for the tantala factor

SiO_2	49.4	7.3	361
Al_2O_3	7.05	12.1	85
MgO	36.5	13.64	498
Ta_2O_5	7.05	X	7.05X
			944+7.05X

But experimentally UARL glass 155 = 15.675×10^6 psi = 1081 kilobars

$$\therefore Ta_2O_5 \text{ contribution} = \frac{1081-944}{7.05} = \frac{137}{7.05} = 19.4 \text{ kilobars/mol}$$

30. Using the data for UARL glass #67 to check the tantala factor just derived

SiO_2	54.7	7.3	399
Al_2O_3	15.3	12.1	185
MgO	29.3	13.64	400
Ta_2O_5	0.76	19.4	15
			999 kilobars calc.

But actual experimental value for UARL 67 = 14.43×10^6 psi = 995 kilobars exp.

APPENDIX I (Cont'd)

31. Using the experimental data for UARL 412 to check both lanthana and beryllia factors

	Mol %	Kilobars/Mol	Contributions
SiO_2	40	7.3	292
Al_2O_3	15	12.1	182
MgO	15	13.64	205
La_2O_3	15	18.5	278
BeO	15	19.0	285
			1242 kilobars calc.

But UARL glass 412 experimentally = 17.92×10^6 psi = 1236 kilobars exp.

32. Using the experimental data for UARL 276 to check both lanthana and beryllia factors

SiO_2	50	7.3	365
Al_2O_3	8.33	12.1	101
Li_2O	8.33	7.0	58
La_2O_3	8.33	18.5	154
BeO	25	19.0	475
			1153 kilobars calc.

But experimentally UARL 276 = 15.82×10^6 psi = 1091 kilobars exp.

33. Using the experimental data for UARL 232 to check yttria and ceria factors simultaneously

SiO_2	48	7.3	350
Al_2O_3	13.33	12.1	161
MgO	26.67	13.64	364
Y_2O_3	10	28.6	286
Ce_2O_3	2	19.6	39
			1200 kilobars calc.

But experimentally UARL glass 232 = 17.62×10^6 psi = 1215 kilobars exp.

34. Using the experimental data for UARL glass 236 to check simultaneously yttria and ceria factors

SiO_2	43	7.3	314
Al_2O_3	15	12.1	182
MgO	30	13.64	409
Y_2O_3	10	28.6	286
Ce_2O_3	2	19.6	39
			1230 kilobars calc.

Experimentally UARL 236 has a value = 17.83×10^6 psi = 1229 kilobars exp.

APPENDIX I (Cont'd)

35. Check of value found experimentally for UARL 494 glass against calculated value (CaO, Y_2O_3, CoO)

	Mol %	Kilobars/Mol	Contributions
SiO_2	65	7.3	475
MgO	12	13.64	164
CaO	12	11.45	137
Y_2O_3	10	28.6	286
CoO	1.0	11	11
			1073 kilobars calc.

But experimentally UARL glass 494 = 15.55×10^6 psi = 1069 kilobars exp.

36. Check of experimental value for UARL 480 glass against calculated value (CaO, Y_2O_3, BeO)

SiO_2	56.2	7.3	410
MgO	4.08	13.64	56
CaO	12.25	11.45	140
Y_2O_3	10.22	28.6	292
BeO	16.33	19.0	310
CoO	1.02	11	11
			1219 kilobars calc.

But experimentally UARL 480 = 18.12×10^6 psi = 1250 kilobars exp.

37. Determination of zinc oxide modulus factor from experimental data for UARL 266 glass

SiO_2	25	7.3	183
Al_2O_3	15	12.1	181
MgO	15	13.64	205
Li_2O	15	7.0	105
CaO	15	11.45	172
ZnO	15	X	15X
			846+15X

But experimentally UARL glass 266 = 16.73×10^6 psi = 1154 kilobars exp.

$$\therefore \text{ zinc oxide factor} = \frac{1154-846}{15} = \frac{308}{15} \cong 20 \text{ kilobars/mol}$$

Other calculations show 19.8 to 20.1

APPENDIX I (Cont'd)

38. Comparing experimental and calculated modulus for UARL 334 glass

	Mol %	Kilobars/Mol	Contributions
SiO_2	35	7.3	256
Al_2O_3	15	12.1	182
MgO	30	13.64	409
La_2O_3	10	18.6	186
ZnO	10	20.0	200
			1233 kilobars calc.

But experimentally UARL 334 glass has a modulus = 17.48×10^6 psi = 1206 kilobars exp.

39. Comparing experimental and calculated moduli for UARL glass 304

SiO_2	35	7.3	256
Al_2O_3	15	12.1	182
MgO	30	13.64	409
ZnO	10	20.0	200
Y_2O_3	10	28.6	286
			1333 kilobars calc.

But experimentally UARL 304 = 19.23×10^6 psi = 1326 kilobars exp.

40. Calculation of modulus expected from UARL glass 495 and comparison with experimental value

SiO_2	57	7.3	416
MgO	12	13.64	164
CaO	12	11.45	137
ZnO	8	20.0	160
Y_2O_3	10	28.6	286
CoO	1	11	11
			1174 kilobars calc.

But experimentally UARL 495 glass has a modulus = 17.24×10^6 psi = 1189 kilobars exp.

41. Comparison of calculated and experimental values for UARL 337 (appreciable number of crystals)

SiO_2	30	7.3	219
Al_2O_3	15	12.1	182
MgO	30	13.64	409
ZnO	12.5	20.0	250
Y_2O_3	12.5	28.6	358
			1418 kilobars calc.

But experimentally UARL glass 337 = 20.9×10^6 psi = 1441 kilobars exp.

APPENDIX I (Cont'd)

42. Check of experimental and calculated values for UARL 274

	Mol %	Kilobars/Mol	Contributions
SiO_2	25	7.3	183
Al_2O_3	15	12.1	181
Li_2O	15	7.0	105
MgO	15	13.64	205
BeO	15	19.0	285
ZnO	15	20.0	300
			1259 kilobars calc.

But experimentally UARL glass = 17.58×10^6 psi = 1212 kilobars exp.

43. Comparison of experimental and calculated values for UARL 257 glass

SiO_2	40	7.3	292
Al_2O_3	12	12.1	145
MgO	12	13.64	264
Li_2O	12	7.0	84
ZnO	12	20.0	240
La_2O_3	12	18.6	223
			1248 kilobars calc.

But experimentally UARL glass 257 = 18.06×10^6 psi = 1245 kilobars exp.

44. Comparison of experimental and calculated values for UARL glass 492

SiO_2	47	7.3	343
Al_2O_3	17	12.1	206
MgO	17	13.64	232
Li_2O	3	7.0	21
ZnO	6	20.0	120
Y_2O_3	10	28.6	286
			1208 kilobars calc.

But experimentally UARL glass 429 has a modulus = 18.55×10^6 = 1279 kilobars exp.

45. Check of experimental and calculated values for UARL 360

SiO_2	39	7.3	275
Al_2O_3	12	12.1	145
MgO	24	13.64	327
Li_2O	6	7.0	42
ZnO	6	20.0	120
Y_2O_3	10	28.6	286
CoO	3	11	33
			1228 kilobars calc.

But experimentally UARL 360 has a modulus = 18.19×10^6 psi = 1255 kilobars exp.

APPENDIX I (Cont'd)

46. Check of experimental and calculated values of UARL 329A glass (ZnO, ZrO_2, Y_2O_3)

	Mol %	Kilobars/Mol	Contributions
SiO_2	22.22	7.3	162
Al_2O_3	11.11	12.1	134
MgO	22.22	13.64	303
Li_2O	11.11	7.0	78
ZnO	11.11	20.0	222
ZrO_2	11.11	23.8	264
Y_2O_3	11.11	28.6	317
			1480 kilobars calc.

But experimentally UARL glass 329A has a modulus = 21.985 x 10^6 psi = 1516 kilobars exp.

47. Checking the experimental value for UARL 336 against its calculated value

SiO_2	35	7.3	256
Al_2O_3	15	12.1	182
Y_2O_3	10	28.6	286
BeO	30	19.0	570
ZnO	10	20.0	200
			1494 kilobars calc.

But UARL 336 glass has an experimentally determined modulus = 20.95 x 10^6 psi = 1445 kilobars

48. Comparison of calculated and experimental modulus for UARL 333

SiO_2	39	7.3	285
Al_2O_3	12	12.1	145
MgO	25	13.64	341
ZnO	12	20.0	240
Y_2O_3	12	28.6	343
			1354 kilobars calc.

But experimentally UARL 333 has a modulus = 18.9 x 10^6 psi = 1303 kilobars exp.

49. Comparison of calculated and experimental modulus for UARL glass 331

SiO_2	39	7.3	285
Al_2O_3	12	12.1	145
ZnO	12	20.0	240
Y_2O_3	12	28.6	343
BeO	25	19.0	475
			1488 kilobars calc.

But experimentally UARL 331 has a modulus = 20.85 x 10^6 psi = 1438 kilobars exp.

APPENDIX I (Cont'd)

50. Comparison of calculated and experimental moduli for UARL 471 glass

	Mol %	Kilobars/Mol	Contributions
SiO_2	25	7.3	183
Al_2O_3	8	12.1	97
MgO	15	13.64	205
Li_2O	15	7.0	105
CaO	10	11.45	115
ZnO	15	20.0	300
Y_2O_3	7	28.6	200
B_2O_3	5	7.2	36
			1241 kilobars calc.

But experimentally UARL 471 glass has a modulus = 17.90×10^6 psi = 1235 kilobars exp.

51. Comparison of calculated and experimental moduli for UARL 464

SiO_2	25	7.3	182.5
MgO	15	13.64	197.4
Li_2O	15	7.0	105
CaO	15	11.45	172
ZnO	10	20.0	200
Y_2O_3	5	28.6	143
B_2O_3	15	7.2	108
			1108 kilobars calc.

But experimentally UARL 464 glass has a modulus = 16.12×10^6 psi = 1112 kilobars exp.

52. Computation of the contribution made by titania to the modulus UARL 501

SiO_2	30	7.3	219
MgO	20	13.64	263
Li_2O	2	7.0	14
CaO	12	11.45	137
Y_2O_3	12	28.6	334
B_2O_3	8	7.2	58
TiO_2	11	X	11X
ZrO_2	4.5	23.8	117
CoO	.5	11	6
			1147+11X

But experimentally UARL 501 has a modulus = 19.02×10^6 psi = 1312 kilobars

$$\therefore \text{ titania factor} = \frac{1312-1147}{11} \cong 15 \text{ kilobars/mol}$$

APPENDIX I (Cont'd)

53. Calculation (in advance of preparation) of modulus to be expected from UARL 500

	Mol %	Kilobars/Mol	Contributions
SiO_2	30	7.3	219
MgO	20	13.64	273
Li_2O	3	7.0	21
CaO	15	11.45	172
Y_2O_3	12	28.6	343
B_2O_3	8	7.2	58
TiO_2	8	15	120
ZrO_2	3.66	23.8	87
CoO	.33	11	4
			1297 kilobars calc.

But UARL 500 glass when made actually had a modulus = 18.97×10^6 psi = 1309 kilobars exp.

54. Comparison of modulus to be expected from UARL 499 (in advance of preparation) with that actually found

SiO_2	40	7.3	292
Al_2O_3	2.66	12.1	32
MgO	18	13.64	246
Li_2O	2	7.0	14
CaO	16	11.45	183
ZrO_2	4	23.8	95
Y_2O_3	10	28.6	286
TiO_2	7	15	105
CoO	.33	11	4
			1257 kilobars calc.

But UARL 499 glass has a modulus = 19.50×10^6 psi = 1345 kilobars exp.

55. Comparison of calculated value for UARL 449 with value found experimentally

SiO_2	25	7.3	183
MgO	20	13.64	273
Li_2O	6	7.0	42
CaO	15	11.45	172
ZnO	4	20	80
Y_2O_3	12	28.6	343
B_2O_3	13	7.2	94
CuO	2	11	22
TiO_2	3	15	45
			1254 kilobars calc.

Experimentally UARL 449 glass = 18.08×10^6 psi = 1247 kilobars exp.

APPENDIX I (Cont'd)

56. Checking predicted and calculated values for Loewenstein (Ref. 9) Glass 73

	Mol %	Kilobars/Mol	Contributions
SiO_2	47.2	7.3	344
Al_2O_3	4.7	12.1	57
CaO	17.8	11.45	204
MgO	14.3	13.64	199
ZnO	4.7	20	94
TiO_2	11.2	15	168
			1066 kilobars calc.

Actually this glass Loewenstein #73 has a modulus = 1017 kilobars exp.

57. Calculation (in advanced preparation) of modulus to be expected from UARL 503 glass and comparison with that found experimentally

SiO_2	39	7.3	285
MgO	15	13.64	205
Li_2O	2	7.0	14
CaO	15	11.45	172
ZrO_2	6	23.8	143
Y_2O_3	10	28.6	286
CoO	1	11	11
TiO_2	12	15	180
			1296 kilobars calc.

But experimentally UARL 503 glass shows a modulus = 19.55×10^6 psi = 1348 kilobars exp.

58. Computation of the contribution of thoria to the modulus UARL 502

SiO_2	45	7.3	328.5
MgO	12	13.64	154
Li_2O	2	7.0	14
CaO	12	11.45	137
Ce_2O_3	2	19.6	39.2
ZrO_2	2	23.8	47.6
Y_2O_3	10	28.6	286
TiO_2	10	15	150
CoO	1	11	11
ThO_2	4	X	4X
			1168+4X kilobars

But experimentally UARL 502 glass has a modulus = 19.02×10^6 psi = 1312 kilobars

$$\therefore \; ThO_2 \text{ factor} = \frac{1312-1168}{4} = 36 \text{ kilobars/mol}$$

APPENDIX I (Cont'd)

All modulus calculations and computed moduli factors are for quenched samples and not for heat treated samples such as those used in Klaus Leopold Loewenstein, U.S. Patent 3,060,041 - Example 7. Such samples have moduli approximately 2 x 10^6 psi higher.