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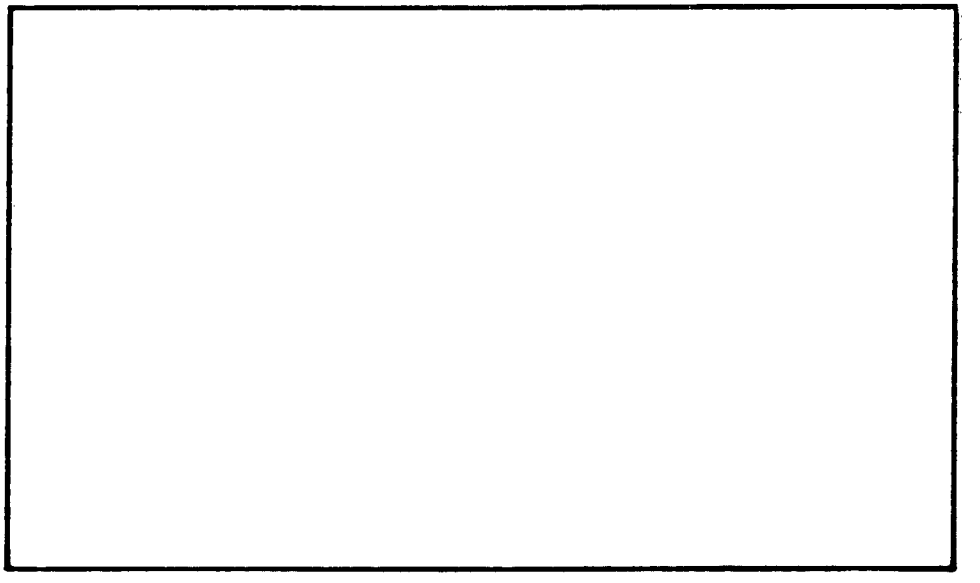

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION - A textron COMPANY

BELL AEROSYSTEMS COMPANY

THERMAL AND MECHANICAL TESTING OF FOAM ALUMINA AND FOAM ZIRCONIA

BLR 61-15(M)

Revision A

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Contract: Company R&D

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TABLES

I. INTRODUCTION

A test program was conducted on alumina foam and zirconia foam manufactured by Ipsen Industries, Incorporated, Rockford, Illinois. The purpose of this program was to determine the possibility of using these materials as insulating panels for high temperature applications. The test temperatures in this program were limited to 3500°F.

The mechanical properties determined in this program were crushing strength at room temperature and modulus of rupture at room temperature, at 1500°F, and at 2500°F. Thermal tests conducted were thermal conductivity and thermal exposure.

The alumina foam had a nominal density of 37 lb/cu ft and the zirconia foam of 45 lb/cu ft.

II. TEST RESULTS

A. MODULUS OF RUPTURE

Table I gives the modulus of rupture and deflection data for alumina foam and zirconia foam at room temperature, at 1500°F, and at 2500°F. At 1500°F two methods were used to introduce the specimens into the furnace. The specimen was either placed directly into the hot furnace chamber, or the specimen was placed in the cold furnace chamber which was then slowly heated to test temperature. The zirconia specimens which were placed in the hot chamber were very weak and could not support the weight of the push bar. The zirconia specimens placed in the cold chamber and heated slowly to 1500°F did not show much improvement over the other zirconia specimens, although a rupture value was obtained for one specimen.

The zirconia specimens tested at 2500°F were placed in the test chamber while it was cold and were heated slowly to test temperature. Four specimens were tested, none could support the weight of the push bar alone.

The alumina specimens tested at 1500°F were introduced directly into the hot chamber. Modulus values were obtained on the two specimens tested. At 2500°F, the alumina specimens were brought to temperature slowly. However, of the three specimens tested, none could support the weight of the test bar alone.

B. CRUSHING STRENGTH

Table II gives the results of crushing strength tests on alumina foam and zirconia foam at room temperature.

C. THERMAL CONDUCTIVITY

Table III gives the results of the thermal conductivity determinations for the alumina and zirconia foam materials. Figure 1 is a graph of the thermal conductivity values for the two materials.

D. THERMAL EXPOSURE

Table IV presents failure data due to thermal exposure for the alumina and zirconia foam specimens. Failure in this test is defined as cracking of the panel, fragmentation, or a complete separation of the fractured parts.

Tables V through IX present time-temperature data for alumina and zirconia foam panels at several test temperatures. Time-temperature data for the zirconia foam panel with the bonded zirconia foam cubes are given in Table X.

III. TEST EQUIPMENT AND PROCEDURE

A. MODULUS OF RUPTURE

Modulus of rupture tests were conducted in a furnace heated with silicon carbide elements. The test specimen, 7 in. long x 1 in. wide x 1/2 in. thick, was supported on a ceramic base. Two point loading was used. The base had two semi-circular ridges spaced 6 inches apart center to center. A ceramic load block, with ridges two inches apart, was used as the two-point load mechanism. Deflection measurements were made with a linear differential transformer located below the furnace. A ceramic rod transferred the movement from the specimen to the transformer. Loading data, determined by a load cell and the deflection data were simultaneously plotted on an X-Y recorder tape.

B. CRUSHING STRENGTH

Crushing strength determinations were made at room temperature on 1 in. x 1 in. x 1 in. ceramic foam cubes in accordance with ASTM C354-54T.

C. THERMAL CONDUCTIVITY

The thermal conductivity values were determined by a comparative axial heat flow method. Min-K 1301 (Johns Manville Corporation) was used as the standard. The foam specimen was heated with a silicon carbide plate. The Min-K 1301 was placed on top of the foam. A soft Fiberfrax pad was placed on the Min-K, and a water cooled copper heat sink was placed over the Fiberfrax pad. Temperature measurements were made at the hot and cold surfaces of the foam specimen and the

Min-K specimen. Radial heat losses were minimized by the use of powder insulation around the test set up. The system was operated for 18 hours to insure equilibrium conditions. Periodic temperature measurements were made to ascertain this equilibrium. The thermal conductivity was calculated as follows:

$$K_1 = \frac{A_2 \Delta t_2 L_1 K_2}{A_1 \Delta t_1 L_2}$$

where:

K_1 = thermal conductivity of the ceramic foam (BTU in/hr ft^2 F)

K_2 = thermal conductivity of Min-K 1301

A_1 = cross sectional area of ceramic foam specimen (ft^2)

A_2 = cross sectional area of Min-K 1301 specimen (ft^2)

Δt_1 = temperature differential between hot and cold surfaces of ceramic foam (F)

Δt_2 = temperature differential between hot and cold surfaces of the Min-K 1301 specimen (F)

L_1 = thickness of ceramic foam specimen (In)

L_2 = thickness of Min-K 1301 specimen (In)

D. THERMAL EXPOSURE

The test specimens were nominally 4-1/2 in. x 4-1/2 in. x 1/2 in. thick. Thermocouples were located on the cold surface of each specimen at depths of 1/3 and 2/3 of the panel thickness, and just under the hot surface. Iridium - iridium - 40% rhodium thermocouples were used where temperatures in excess of 3000°F were encountered. Platinum - platinum 10% rhodium couples were used for the range of 2000°F to 3000°F. Chromel - alumel couples were used at temperatures of 2400°F and below. Thermocouple output was recorded on a Leeds and Northrup 10 - channel

recorder. Interval between individual measurements was 3 seconds. All specimens were weighed and measured before and after testing.

The specimen was placed in a firebrick test fixture, open on the top and bottom. A 1/4-inch ledge at the bottom supported the specimens. The cold surface of the test specimen was insulated with Thermoflex fibrous insulant. The firebrick fixture was supported in an angle iron frame. The test set-up was suspended over an oxy-acetylene furnace and was raised and lowered by steel cables running through a pulley. The opening of the furnace was bricked in to provide a reduced opening of 4-1/4 inches x 4-1/4 inches.

The furnace was preheated for approximately 45 minutes before the start of the test. The test fixture with the specimen in place was then lowered over the opening in the furnace. The heating rate, predetermined by tests on sample specimens, was recorded as was the temperature history of the complete test. The hot surface temperature was controlled by adjustment of the height of the specimen over the furnace.

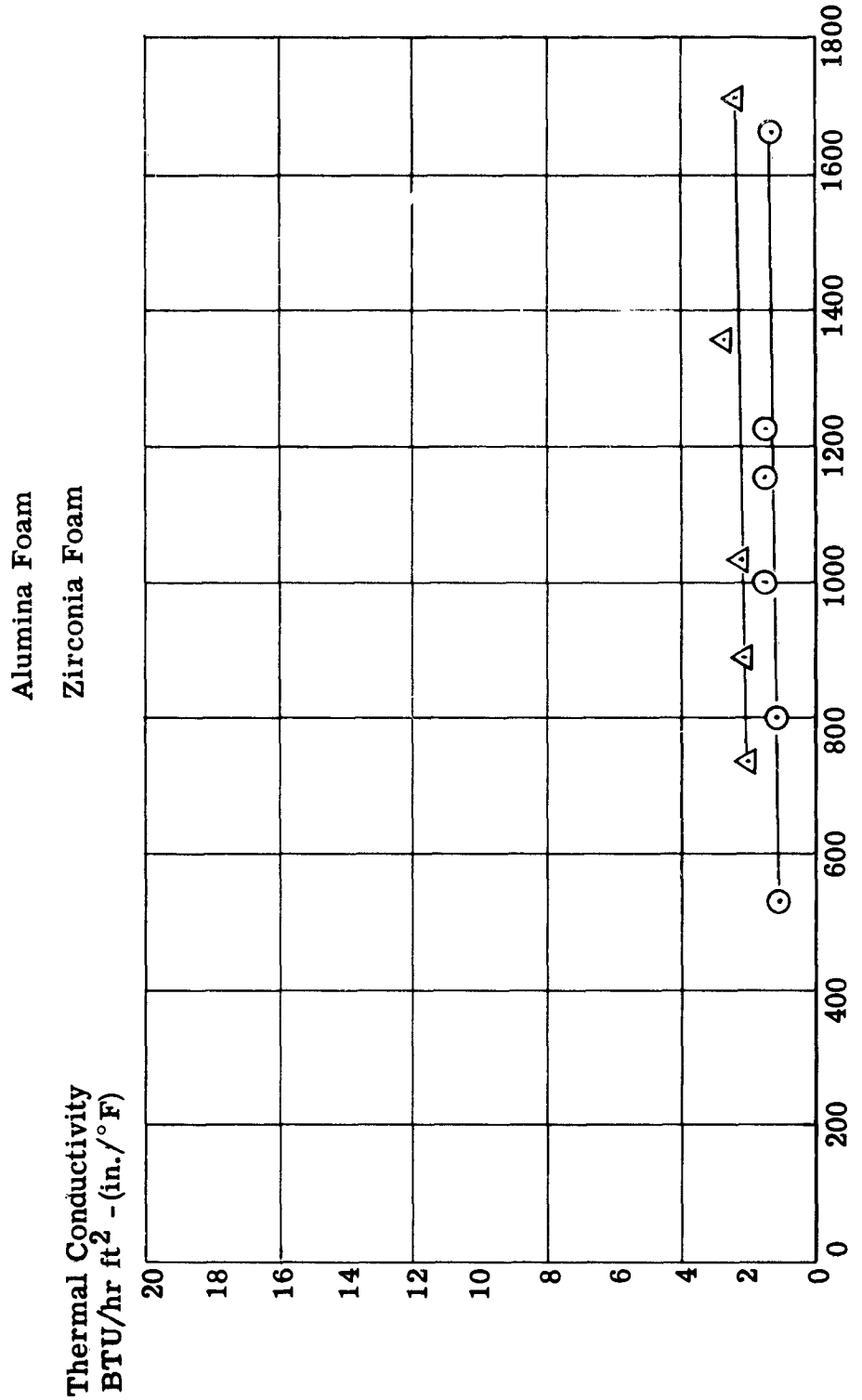

Figure 1. Thermal Conductivity of Foam Alumina and Foam Zirconia

TABLE I

MODULUS OF RUPTURE AND DEFLECTION DATA
FOR FOAM ZIRCONIA AND FOAM ALUMINA

Temperature (°F)	Foam Zirconia		Foam Alumina	
	MR (psi)	Deflection (in.)	MR (psi)	Deflection (in.)
Room	325	0.0138	439	0.0096
	349	0.0098	326	0.0070
	285	0.0138	451	0.0096
	376	0.0126	504	0.0051
	298	0.0132	430	0.0089
	464	0.0164	481	0.0085
	406	0.0138	336	0.0052
	300	0.0108	521	0.0081
	544	0.0140	640	0.0095
1500	86(1)	0.0012	302(2)	0.0045
	(2,3) 2 specimens broke with no load		93	0.0015
	(1,3) 2 specimens broke with no load			
2500	(1,3) 4 specimens broke with no load		(1,3) 3 specimens broke with no load	

NOTES: (1) Specimen was placed in the cold test chamber. The chamber was then slowly brought up to test temperature.

(2) Specimen was introduced directly into the heated furnace and soaked for 5 minutes before testing.

(3) Broke under weight of push bar. This indicates a modulus of rupture value between 0 and 60 psi.

TABLE II

CRUSHING STRENGTH OF ALUMINA FOAM AND ZIRCONIA FOAM AT ROOM TEMPERATURE (ASTM C354-54T)

Material	Crushing Strength (psi)
Alumina Foam	1005
	1415
	1310
	1090
	700
	1515
	1215
Average of Seven Specimens	1179
Zirconia Foam	865
	560
	500
	588
	827
	816
	403
Average of Seven Specimens	651

TABLE III

THERMAL CONDUCTIVITY OF ALUMINA FOAM AND ZIRCONIA FOAM

Material	Mean Temperature (°F)	Thermal Conductivity (BTU·in./ft^2·hr·°F)
Alumina	735	2.1
	890	2.1
	1035	2.2
	1360	2.6
	1715	2.4
Zirconia	535	1.1
	800	1.1
	1000	1.5
	1155	1.5
	1230	1.5
	1665	1.4

TABLE IV

THERMAL EXPOSURE RESULTS FOR
ALUMINA FOAM AND ZIRCONIA FOAM

Material	Specimen No.	Exposure Temperature (°F)	Conditions Time (minutes)	Heat Resistance
Zirconia Foam	6	1500	15	No failures or changes
		1800	15	No failures or changes
		2000	15	No failures or changes
		2300	15	No failures or changes
		2600	15	No failures or changes
		2950	15	Numerous cracks observed upon cooling.
Zirconia Foam	7	1500	15	No failures or changes
		1800	15	No failures or changes
		2000	15	No failures or changes
		2300	15	No failures or changes
		2600	15	No failures or changes
		2950	15	No failures or changes This specimen was heated and cooled very slowly. In order to test under greater thermal shock conditions, the cycle of 2-1/2 minutes for heating, hold for 15 minutes at temperature, and cool in 2-1/2 minutes was used on a rerun of this specimen (see below).
Zirconia Foam	7 Rerun	1500	15	No failures or changes
		1800	15	No failures or changes
		2000	15	No failures or changes
		2300	15	No failures or changes Two failures upon cooling. One crack was 1-1/2 in. long, the second 1 in. long. This panel was very weak after this test program.

TABLE IV (Continued)

Material	Specimen No.	Exposure Temperature (°F)	Conditions Time (minutes)	Heat Resistance
Alumina Foam	2	1500	15	No failures or changes
		1800	15	No failures or changes
		2000	15	No failures or changes
		2300	15	No failures or changes
		2600	15	No failures or changes
		2950	15	No failures or changes This panel was quite strong after this test program.
Alumina Foam	7	1500	15	No failure or changes
		1800	15	No failure or changes
		2000	15	No failure or changes
		2300	15	No failure or changes
		2600	15	No failure or changes
		2900	15	No failure or changes
Zirconia Foam	9	3000-3500(1)	15	One crack, 2 in. long, through panel thickness; remainder of panel was quite strong.
Alumina Foam	6	3000-3500(1)	15	Specimen cracked across width in one place; three other localized cracks occurred. Specimen broke easily along crack. Otherwise it was quite strong.
Zirconia Foam with attached Zirconia Foam Cubes		2000	15	No failures visible
		2950	15	No failure visible
		3500	After approximately two minutes, the specimen holding fixture failed and the panel dropped into the furnace.	

Note (1): Due to difficulties in temperature measurement, the exact exposure temperature could not be ascertained. However, it was determined that the test temperature was between 3000°F and 3500°F.

TABLE V

TIME-TEMPERATURE DATA FOR ALUMINA FOAM SPECIMEN NO. 7 TESTED AT 1500°F FOR 15 MINUTES

Time	Thermocouple Number	Temperature (°F)	Time	Thermocouple Number	Temperature (°F)
0	1	297	5-1/2	1	1230
	2	335		2	1343
	3	376		3	1360
	4	541		4	1486
1	1	516	7	1	1215
	2	620		2	1326
	3	697		3	1330
	4	1326		4	1485
1-1/2	1	711	10	1	1200
	2	881		2	1326
	3	1003		3	1330
	4	1486		4	1477
2	1	910	15	1	1225
	2	1083		2	1339
	3	1154		3	1352
	4	1576		4	1494
2-1/2	1	1068	16-1/2	1	1219
	2	1217		2	1337
	3	1241		3	1352
	4	1486		4	1494
3-1/2	1	1210	17	1	1198
	2	1335		2	1326
	3	1352		3	1326
	4	1552		4	1360
4-1/2	1	1236	17-1/2	1	1196
	2	1356		2	1281
	3	1360		3	1275
	4	1510		4	1263
			19	1	1057
				2	1107
				3	1100
				4	1039

TABLE VI

TIME-TEMPERATURE DATA FOR ALUMINA FOAM
SPECIMEN NO. 2 TESTED AT 2600°F FOR 15 MINUTES

Exposure Time (minutes)	Thermocouple Number	Temperature (°F)	Exposure Time (minutes)	Thermocouple Number	Temperature (°F)
0	1	142	5-1/2	1	2032
	2	374		2	2287
	3	409		3	2307
	4	453		4	2593
1/2	1	354	6	1	2061
	2	452		2	2284
	3	511		3	2277
	4	649		4	2547
1	1	444	7	1	2052
	2	606		2	2294
	3	707		3	2307
	4	967		4	2593
2	1	781	12	1	2090
	2	1084		2	2297
	3	1216		3	2287
	4	1663		4	2564
3	1	1286	17	1	2074
	2	1640		2	2307
	3	1760		3	2309
	4	2203		4	2602
4	1	1716	21	1	2097
	2	2027		2	2323
	3	2100		3	2323
	4	2457		4	2609
5	1	1966	21-1/2	1	2044
	2	2232		2	2222
	3	2278		3	2175
	4	2562		4	2265

TABLE VI (Continued)

Exposure Time (minutes)	Thermocouple Number	Temperature (°F)	Exposure Time (minutes)	Thermocouple Number	Temperature (°F)
22-1/2	1	1808	25	1	1256
	2	1917		2	1285
	3	1886		3	1250
	4	1917		4	1199
23-1/2	1	1576			
	2	1635			
	3	1585			
	4	1537			

TABLE VII

TIME-TEMPERATURE DATA FOR ALUMINA FOAM
SPECIMEN NO. 2 TESTED AT 2900°F FOR 15 MINUTES

Exposure Time (minutes)	Thermocouple Number	Temperature (°F)	Exposure Time (minutes)	Thermocouple Number	Temperature (°F)
0	1	323	6	1	1952
	2	400		2	2143
	3	444		3	2267
	4	526		4	2492
1/2	1	382	7	1	2043
	2	511		2	2228
	3	566		3	2342
	4	740		4	2574
1	1	493	10	1	2237
	2	675		2	off scale
	3	750		3	2567
	4	1016		4	2809
2	1	795	10-1/2	1	2265
	2	1034		2	—
	3	1114		3	2612
	4	1440		4	2884
3	1	1133	15	1	—
	2	1396		2	—
	3	1457		3	2725
	4	1780		4	3014
4	1	1472	18	1	—
	2	1744		2	—
	3	1873		3	2642
	4	2192		4	2870
5	1	1779	25	1	—
	2	1997		2	—
	3	2124		3	2657
	4	2372		4	2915

TABLE VII (Continued)

Exposure Time (minutes)	Thermocouple Number	Temperature (°F)	Exposure Time (minutes)	Thermocouple Number	Temperature (°F)
25-1/2	1	–	27	1	1903
	2	–		2	1903
	3	2582		3	1935
	4	2733		4	1889
26	1	2240	27-1/2	1	1745
	2	2288		2	1735
	3	2357		3	1726
	4	2386		4	1669
26-1/2	1	2071			
	2	2081			
	3	2132			
	4	2117			

TABLE VIII

TIME-TEMPERATURE DATA FOR ZIRCONIA FOAM
SPECIMEN NO. 7 TESTED AT 1500°F FOR 15 MINUTES

Exposure Time (minutes)	Thermocouple Number	Temperature (°F)	Exposure Time (minutes)	Thermocouple Number	Temperature (°F)
0	1	104	25-1/2	1	1242
	2	126		2	1270
	3	191		3	1390
	4	216		4	1515
3	1	182	28-1/2	1	1240
	2	221		2	1270
	3	312		3	1390
	4	387		4	1520
7	1	422	29-1/2	1	1240
	2	459		2	1268
	3	571		3	1377
	4	620		4	1477
10	1	645	33-1/2	1	1057
	2	724		2	1053
	3	875		3	1153
	4	1039		4	1136
13-1/2	1	1068	37	1	823
	2	1140		2	789
	3	1352		3	772
	4	1454		4	820
15	1	1180			
	2	1233			
	3	1360			
	4	1520			
17	1	1225			
	2	1264			
	3	1386			
	4	1515			

TABLE IX

TIME-TEMPERATURE DATA FOR ZIRCONIA FOAM
SPECIMEN NO. 7 TESTED AT 2950°F FOR 15 MINUTES

Exposure Time (minutes)	Thermocouple Number	Temperature (°F)	Exposure Time (minutes)	Thermocouple Number	Temperature (°F)
0	1	183	4	1	749
	2	202		2	861
	3	312		3	1115
	4	329		4	1387
1/2	1	220	6	1	1403
	2	255		2	1577
	3	378		3	1894
	4	472		4	2182
1	1	268	8	1	1830
	2	313		2	1989
	3	439		3	2272
	4	539		4	2474
1-1/2	1	317	9	1	1930
	2	371		2	2099
	3	483		3	2392
	4	583		4	2565
2	1	380	11	1	2058
	2	434		2	2224
	3	563		3	2535
	4	699		4	2715
3	1	518	12	1	2118
	2	588		2	2281
	3	775		3	2595
	4	959		4	2753
3-1/2	1	622	14	1	2179
	2	710		2	2345
	3	968		3	2675
	4	1242		4	2826

TABLE IX (Continued)

Exposure Time (minutes)	Thermocouple Number	Temperature (°F)	Exposure Time (minutes)	Thermocouple Number	Temperature (°F)
15	1	2196	36	1	1619
	2	2375		2	1805
	3	2700		3	1886
	4	2860		4	1891
16	1	2224	38	1	1365
	2	2400		2	1468
	3	2738		3	1528
	4	2898		4	1487
20	1	2214	40	1	1157
	2	—		2	1234
	3	2799		3	1225
	4	2951		4	1182
25	1	2172	43	1	920
	2	—		2	935
	3	2806		3	868
	4	2951		4	914
30	1	2157			
	2	—			
	3	2799			
	4	2943			
31-1/2	1	2152			
	2	—			
	3	2791			
	4	2913			
32-1/2	1	2027			
	2	2275			
	3	2535			
	4	2617			
34	1	1867			
	2	2128			
	3	2362			
	4	2467			