

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 1911

PHYSICAL PROPERTIES AT ELEVATED TEMPERATURE
OF SEVEN HOT-PRESSED CERAMICS

By James J. Gangler, Chester F. Robards
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SUMMARY

An investigation of seven hot-pressed ceramics for possible gas-turbine application was undertaken. The properties, short-time tensile strength, thermal-shock resistance, coefficient of liner expansion, and density were determined. The compositions of the ceramics were magnesium oxide, titanium carbide, zirconium carbide, boron carbide, 85-percent silicon carbide plus 15-percent boron carbide, zircon, and zirconia stabilized with 6-percent lime. The short-time tensile strengths of these ceramics were determined at temperatures of 1800° and 2200° F. Resistance to thermal shock was determined at 1800°, 2000°, 2200°, and 2400° F. The thermal-expansion characteristics of these bodies were studied up to 1100° F.

Zirconium carbide had a short-time tensile strength of 15,850 pounds per square inch at 2200° F, which was the highest measured at this temperature; however, it exhibited very poor resistance to oxidation. Boron carbide had a short-time tensile strength of 22,550 pounds per square inch at 1800° F, the highest strength at this temperature. The evaluation of strength of boron carbide at 2200° F was unsuccessful. Titanium carbide had the best resistance to thermal shock and was the most promising of the seven compositions investigated as it had strengths of 15,850 pounds per square inch at 1800° F and 9400 pounds per square inch at 2200° F. Hot-pressing of these seven highly refractory bodies indicated that a density of at least 93 percent of theoretical density could be obtained.

INTRODUCTION

Service requirements in a gas-turbine or jet engine are severe because they involve conditions of high tensile stress, exposure to high temperatures for prolonged periods of time, and sudden temperature fluctuations upon starting and stopping. A few metallic alloys are satisfactory in these respects up to an operating temperature of 1500° F, but their strength will, in general, decrease rapidly above

this temperature. Ceramics have a number of inherent advantages over metallic alloys above 1500° F. The melting points are generally much higher and the bulk densities are low, which is a desirable property in applications where centrifugal force is present. Oxide ceramics are inert to further oxidation and therefore are more resistant to corrosion in usual jet atmospheres than metallic alloys. Some porcelain ceramics are stronger in tension at elevated temperatures than metallic alloys and have negligible creep (reference 1). Both the oxide- and carbide-type ceramics, on the other hand, have less resistance to failure from thermal shock than metallic alloys. When a jet engine is started, the temperature of the turbine blades may increase at a rate as high as 130° F per second. In order for a material to have good resistance to thermal shock, it should have high strength, high thermal conductivity, low thermal expansion, and high ductility.

An investigation, which is reported herein, was conducted at the NACA Lewis laboratory to determine tensile strength, resistance to failure by thermal shock, and thermal expansion of seven hot-pressed ceramics that were known to have satisfactory characteristics in one or more of the properties of high melting point, density, strength, thermal conductivity, thermal expansion, or thermal-shock resistance. Chemical analyses of these ceramics were made to determine the amount of free carbon present and to determine if there was a composition change during fabrication. Density determinations were made on each body to determine the effectiveness of the hot-pressing operation.

All ceramics used in this investigation were obtained from the Norton Company, Worcester, Massachusetts.

FABRICATION TECHNIQUES

A number of fabrication techniques are used to produce ceramic products. The common methods of fabricating ceramic products are slip-casting, extrusion, cold-pressing, and hot-pressing. Slip-casting involves pouring the body, the powders of which are suspended in water, into plaster molds. The extrusion method uses a die through which is forced a plastic body. Cold-pressing techniques involve pressing dry or moist powders in a die or in hydrostatically loaded molds. Firing or sintering follows the fabrication procedures. Hot-pressing is the newest but least known and used method in the family of fabrication methods. This method involves the application of a

load at or near the sintering temperature of the material contained in a suitable die, which is usually graphite in the case of ceramics.

The physical properties of ceramic bodies can be appreciably varied by the choice of fabrication technique. Certain properties, such as strength, thermal conductivity, and hardness, depend on the degree of porosity in the fired body. These properties will approach maximum values as the porosity approaches zero; a measure of the porosity is the apparent density of the material. The deviation of apparent density from theoretical density as calculated from crystal-lattice parameters and atomic weights of the component elements may be used to determine the effectiveness of a fabrication technique in reducing porosity. Slip-casting, extrusion, and cold-pressing leave much to be desired in the matter of approaching maximum density in powder products. By the use of one of these three fabrication methods, a body may be produced having density variations, cavities, and segregation of component powders. Hot-pressing, on the other hand, not only is capable of producing a dense body but an article can be pressed to size without warpage from heating. Cavities, caused by bridging of the powders during the pressing operation, are minimized by the elevated temperatures during the fabrication process. Although hot-pressing is not used extensively in ceramic work, the advantages derived from its use recommend it when the material produced is to be of high quality. Hot-pressing is employed to a greater extent in powder metallurgy (references 2 and 3) than in fabrication of ceramics.

Graphite dies are used in hot-pressing of ceramics because of the high temperatures required. The use of graphite dies of practicable size limits the effective pressure on the ceramic compact to approximately 2500 to 10,000 pounds per square inch for temperatures up to 5400° F.

APPARATUS AND PROCEDURE

Tensile-Strength Evaluation

The high-temperature, short-time tensile-strength evaluation unit and the procedure used in this investigation were the same as those described in reference 4. The specimens were radiographically inspected in two planes 90° apart for internal flaws and were inspected by a fluorescent-oil method for external cracks. Only specimens that

did not exhibit flaws were used. All tensile specimens were machined from cylindrical rods 6 inches long and 1 inch in diameter. The finished tensile specimens were 4.50 inches long and had a gage length of 1.25 inches and a gage diameter of 0.50 inch. The diameter of each specimen was measured before and after evaluation in three positions along the gage length and in two planes 90° apart at each position. The average diameter after evaluation was used for the calculation of the tensile strength. Because a thin oxide coating formed on all the carbide specimens, the diameters of these specimens after evaluation were also determined before and after the removal of this oxide coating. The tensile strength of the carbides was calculated on the basis of the average diameter after removal of the oxide coating. The area of the oxide coating did not exceed more than 0.8 percent of the total cross section of any of the carbides except in the case of zirconium carbide. Zirconium carbide appears to have such a high affinity for oxygen that, in spite of the helium atmosphere used to minimize oxidation, the area oxidized was 13 percent and 45 percent of the original cross-sectional area at 1800° and 2200° F, respectively. The unit stress for specimens that did not break within the gage length was calculated using the minimum cross section of the gage length.

A platinum-wound tubular electric furnace 3 inches in diameter was used to heat the specimen at 1800° F; a tubular nonmetallic resistor-bar furnace with the elements on a $4\frac{1}{2}$ -inch-diameter circle was used at 2200° F. Thermocouples of platinum and platinum plus 13-percent rhodium were used for furnace control and all specimen temperature determinations. The oxide tensile specimens were evaluated in an oxidizing atmosphere; the carbides were evaluated in an atmosphere of helium to minimize oxidation. An automatic temperature-control system so controlled the furnaces as to maintain the specimen temperature within $\pm 10^\circ$ at 1800° and 2200° F. A commercial hydraulic-type tensile machine with adapter rods and grips of a high-temperature nickel alloy completed the unit. The tensile machine had an error of less than 0.5 percent over the experimental range of 0 to 4000 pounds.

The tensile specimens and grips were aligned at room temperature under a load of 500 pounds. Misalignment was corrected by gentle tapping of the adapter rods and grips. The degree of alignment was indicated by two sets of diametrically opposite electric strain gages mounted on the gage length of the specimen. The gages were capable of indicating a strain of 1 microinch. Misalignment was maintained

as small as consistent with the eccentricity of specimens and grips. In most cases the maximum calculated bending stress was less than 15 percent of the stress used for alinement.

Approximately one-half of the specimens were soaked an average of 13 hours at soaking temperature before pulling. The remainder were soaked for only 4 hours. The shorter time was instituted in order to minimize any stress-rupture effect that may have been caused by the longer soaking period and yet afford sufficient time to improve alinement and to relieve local stresses. A load of 100 pounds was applied to all specimens during the soaking period. The furnace was then cooled to the evaluation temperature and held for 1/2 hour, after which the specimen was loaded at the rate of 400 pounds per minute until failure occurred.

Thermal-Shock Evaluation

The thermal-shock evaluation of the seven hot-pressed ceramics was conducted in the apparatus and according to the procedure described in reference 4. The thermal-shock specimens were disks 2 inches in diameter and 1/4 inch in thickness. A representative disk of each of the seven compositions as received is shown in figure 1. All specimens were inspected upon their receipt for internal and external flaws by radiographic and fluorescent oil methods, respectively. No flaws were detected.

Each specimen was placed in a preheated furnace at the evaluation temperature for 10 minutes and then cooled in a stream of air at a temperature of 85° F for 5 minutes. This procedure constituted one cycle. If a material successfully withstood 25 cycles at the initial temperature of 1800° F, the evaluation was continued on the same specimen for 25 cycles at each of the temperatures of 2000°, 2200°, and 2400° F or until failure. The appearance of a crack was considered to be a failure. In those cases where failure was suspected at any time during the evaluation, the specimens were radiographically inspected.

A specimen that failed during the heating period of the first cycle was considered to have failed in zero cycles. A specimen that withstood the first heating period but failed during the cooling portion of the cycle was given a thermal-shock resistance of one-half cycle.

Coefficients of Thermal Expansion

The coefficient of linear expansion was determined for each of the seven hot-pressed ceramic bodies by means of a dilatation interferometer. The monochromatic light used was the green radiation of the mercury spectrum with a wave length of 0.0000546 centimeter. Three pyramids of 4 to 5 millimeters in height constituted a single specimen in which the expansion obtained from a reference mark was an average of the expansion of all three specimens. The over-all height of the pyramids was obtained by a micrometer caliper graduated to 0.0001 centimeter. The expansion of the specimens was noted by visually counting the number of interference fringes passing a reference mark on the lower interferometer plate. All temperatures were determined by a chromel-alumel thermocouple, which was positioned beneath the lower interferometer plate, and an indicating potentiometer. The heating rate used was 7.2° F (4° C) per minute. The coefficients were determined in the range from room temperature to 1100° F. The carbides or their oxides reacted with the interferometer plates above this temperature. The use of inert or slightly reducing atmospheres did not prevent a reaction from occurring. Two runs were made for each of two sets of specimens for each composition.

RESULTS AND DISCUSSION

Hot-Pressing

Hot-pressing, generally speaking, is capable of producing metal compacts of zero porosity. This condition is difficult to obtain for ceramics, however, because the optimum sintering temperatures are above the temperatures currently used in hot-pressing. The degree of success in obtaining maximum density by hot-pressing of seven ceramics is presented in table I, which shows the apparent densities of these ceramics. The apparent densities were determined by differential weighing in air and in distilled water at room temperature and correcting to 39.2° F (4° C). Theoretical densities calculated from X-ray data were included for comparative purposes. Hot-pressing produced bodies of at least 93 percent of the theoretical density in all cases.

One of the factors connected with this method of fabrication that tends to prevent the obtaining of maximum density is the presence of excess carbon in the finished body. The chemical analyses of the seven compositions as obtained from a commercial laboratory are presented in

table II. The oxides had free and combined carbon totaling from approximately 0.1 to 1 percent by weight before evaluation. The free carbon found in the oxides was probably caused by carbon from the graphite die penetrating into the compact during fabrication. The carbide compacts had free carbon in amounts of approximately 3 and 4 percent by weight. The relatively high amount of free carbon present in the carbides is probably due to the marked solubility of carbon in some of the carbides during production. For example, titanium carbide and zirconium carbide are reported to dissolve considerable amounts of carbon at elevated temperatures, which are precipitated on cooling (reference 5). A polished and etched section of the titanium carbide body as received is shown in figure 2. The black areas appear to be graphite. Much of the graphite has precipitated out into the grain boundary. A quantity of 4 percent by weight of graphite would result in a surface area having a threefold or fourfold percentage increase in area of graphite. The amount of carbon therefore partly explains the lower-than-theoretical densities.

Tensile-Strength Evaluation

The results obtained in the short-time tensile-strength evaluation of the seven hot-pressed ceramics are presented in table III. In most cases, the bending stresses were less than 15 percent of the tensile stress on the specimen during alignment. Consequently, the tabulated values are lower than the true values if the bending stresses did not decrease with an increase in load, time, and temperature. In general, the highest measured tensile strength obtained for any one composition will be most nearly representative of the true tensile strength.

Boron carbide with a value of 22,550 pounds per square inch showed the highest tensile strength of all the ceramics at 1800° F. The evaluation of the short-time tensile strength of boron carbide at 2200° F was unsuccessful. Three tensile specimens of boron carbide remained intact after being pulled out of the high-nickel-alloy grips at the soaking temperature of 2300° F, although other ceramics were successfully soaked at this temperature. That portion of the grips in contact with the boron carbide specimens initially appeared to have flowed plastically. In order to prevent the grips from failing they were air-cooled to 1950° F while a specimen temperature of 2300° F was maintained. The air-cooled grips, however, still failed. Evidence was then found that a diffusion reaction occurred between the boron carbide specimen and the high-nickel-alloy grips, which resulted in a low-melting phase.

Above 1950° F and under a load of 50 to 100 pounds, the grips could not retain the specimen. Nickel is known to form a eutectic composition with 12-percent boron by weight at 1814° F (reference 6).

Zirconium carbide was the best ceramic in measured strength at 2200° F with a strength of 15,850 pounds per square inch. Because 45 percent of the total area was oxidized, some doubt exists that zirconium carbide will withstand this high unit stress in comparison to the other bodies evaluated, inasmuch as the tensile strength of a ceramic may also be a function of the cross-sectional area of the specimen investigated (reference 7). All the carbides were superior to the oxides in strength at both temperatures, as shown in table III.

Titanium carbide failed at a unit stress of 9400 pounds per square inch at 2200° F.

Zircon was the best in strength of the three oxide-type ceramics at 1800° F. It had a strength as high as 8700 pounds per square inch. Zircon was the only oxide-type ceramic evaluated at 2200° F; it had a tensile strength as high as 3600 pounds per square inch. Magnesium oxide had a tensile strength considered low because both specimens evaluated at 1800° F failed outside of the gage length. Attempts to obtain a tensile strength for magnesium oxide at 2200° F failed. An indication of the room-temperature tensile strength of magnesium oxide is given by specimen 2A3 (table III), which failed at a load of 480 pounds as the alining load was being applied. The unit strength of magnesium oxide at room temperature may thus be 2400 pounds per square inch. Subsequent magnesium oxide specimens were alined under a load of 300 pounds.

The measured strengths of all of the bodies except zirconium carbide decreased from 1800° to 2200° F.

The type and nature of the fractured surface occurring in ceramic tensile bodies is indicative of the mode of failure. The fractures were examined as recommended for electrical porcelains by the A.S.T.M. (reference 8) and the results are reported in table III. In order to interpret table III, a rough fracture is defined as one in which approximately 90 to 100 percent of the surface appears to be granular; in a partly rough fracture, 50 to 90 percent of the surface is granular; and in a smooth fracture, 0 to 50 percent of the surface is granular (reference 9). A wholly granular surface indicates that the entire area was subjected to tension and the entire surface resisted it. This type of fracture for the body of silicon carbide plus boron carbide is illustrated in figure 3. The surface is very rough and granular. In a

specimen containing a cavity, a pin hole, or another flaw, the fracture may start near that flaw or pass through it. The surface near the flaw will be smoother than that part farther away. This type of failure for specimen 4A7, zirconium carbide, indicates that the value for this specimen is low (fig 4). A similar surface for specimen 3A5, titanium carbide, is shown in figure 5. The flaw in this case was a small yellow inclusion. If a specimen fails in that portion within a grip, it may fail by both tension and compression or shear. The resulting surface will have both granular and smooth areas. The fractured surface of a magnesium oxide specimen is shown in figure 6. The surface is almost entirely smooth and conchoidal. Failure occurred in that portion of the specimen under compression within the grips. Because all specimens of magnesium oxide failed exactly in this manner, it is concluded that magnesium oxide will fail in shear before it will fail in tension. The rougher the surface in any one composition, the higher was the tensile strength.

Thermal-Shock Evaluation

The results of the thermal-shock evaluation on the seven hot-pressed bodies are presented in table IV. The compositions are shown in order of decreasing resistance to thermal shock. The carbides, with the exception of boron carbide, are better in resistance to thermal shock than the oxides. Titanium carbide is outstanding in thermal shock resistance. It endured as many as 25 cycles at 1800°, 2000°, and 2200° F and 21 thermal-shock cycles at 2400° F. The severity of this test is indicated by the results obtained for zircon and stabilized zirconia, two ceramic materials commonly known for their good resistance to thermal shock. Zircon failed after one cycle, whereas zirconia stabilized with 6-percent lime shattered into small fragments the instant it was put into the furnace at 1800° F. This sudden failure indicated that perhaps the zirconia was not stabilized, but X-ray diffraction analysis of the crystal structure showed the zirconia was in the cubic or stabilized form. Thermal-expansion curves failed to show inversions characteristic of natural zirconia. Excessive oxidation of the zirconium carbide caused its evaluation to be halted after 22 cycles at 1800° F. Zirconium carbide had not shown any sign of cracking up to that point. An oxidized layer on the surface was blown off during each cooling cycle. A representative sample of each of the seven compositions after its evaluation for thermal-shock resistance is shown in figure 7.

Thermal Expansion

The coefficients of linear expansion of the seven hot-pressed bodies are listed in table V. The expansion curves are shown in figure 9. The data compare well with that in the literature. High thermal expansion is a property of titanium carbide, which shows the best thermal-shock resistance of the materials studied. In contrast to titanium carbide, boron carbide has the lowest-thermal expansion of the carbides, but it is poorest in resistance to thermal shock. Thermal expansion therefore should not be considered alone when investigating possible thermal-shock characteristics of materials, but should be considered in conjunction with other physical properties.

SUMMARY OF RESULTS

The investigation to determine for gas-turbine applications the short-time tensile strength, thermal-shock resistance, thermal expansion, and density of each of seven hot-pressed ceramic bodies gave the following results:

1. Titanium carbide had the best resistance to thermal shock. It endured as many as 25 cycles at 1800°, 2000°, and 2200° F and 21 thermal-shock cycles at 2400° F. Next to zirconium carbide, it was the strongest at 2200° F having a tensile strength of 9400 pounds per square inch.
2. Boron carbide had a tensile strength of 22,550 pounds per square inch at 1800° F. It was the strongest of any ceramic evaluated at this temperature.
3. Zirconium carbide had a tensile strength of 15,850 pounds per square inch at 2200° F, thus it was the strongest at this temperature of the ceramics investigated; however, it exhibited very poor resistance to oxidation.
4. The materials evaluated indicated that the carbides as a class were superior to the oxides in tensile strength. The best oxide composition at 1800° F was zircon with a strength of 8700 pounds per square inch. At 2200° F it had a strength as high as 3600 pounds per square inch.

5. The carbides with the exception of boron carbide also proved to be better than the oxides in thermal-shock resistance. Zircon, the best of the oxide-type ceramics in thermal-shock resistance, withstood only one cycle.

6. Hot-pressing resulted in bodies having densities of at least 93 percent of their theoretical values.

7. The coefficients of linear expansion obtained for the seven materials were in good agreement with the values in the literature.

CONCLUSIONS

The investigation yielded results indicating that titanium carbide is the best of the seven bodies when all the physical properties are considered. It was the best in resistance to thermal shock and has relatively high tensile strength at elevated temperatures. It has relatively high resistance to oxidation. On the other hand, titanium carbide, like the other ceramics investigated is a brittle material and must be handled with care. Because of its good properties of strength and resistance to thermal shock, titanium carbide warrants further consideration as a material in aircraft power plants.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
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TABLE I - DENSITIES OF SEVEN HOT-PRESSED CERAMICS

Specimen	Composition	Theoretical density (gram/cc)	Apparent density (gram/cc)	$\frac{\text{Apparent density} \times 100}{\text{Theoretical density}}$
2A12	Magnesium oxide	3.62 ^a	3.39	93.6
3A8	Titanium carbide	4.91 ^a	4.74	96.5
4A2	Zirconium carbide	6.44 ^a	6.30	97.8
5A11	Boron carbide	2.52 ^b	2.50	99.2
6C12	85-percent silicon carbide, 15-percent boron carbide	-----	3.00	-----
7A11	Zircon	4.72 ^a	4.54	96.2
8A12	Zirconia (stabilized)	6.1 ^c	5.80	95.1

^aCalculated from crystal-structure data in reference 10.

^bDetermined experimentally from a single crystal. Reference 11.

^cNorton Company data.



TABLE II - CHEMICAL ANALYSES OF SEVEN HOT-PRESSED CERAMICS

Specimen	Nominal composition (percent by weight)	Constituents (percent by weight)									
		Magnesium	Titanium	Zirconium	Boron	Silicon	Oxygen	Combined carbon	Free carbon	Total	
2A1	Magnesium oxide	60.02						39.58	0.07	<0.01	99.68
2A12	-----do-----	60.06						39.66	.06	.04	99.82
3A8	Titanium carbide		77.04						17.07	2.76	96.87
4A10	Zirconium carbide			86.22					9.44	4.07	99.73
4A4	-----do-----			85.62					9.63	4.29	99.54
5A4	Boron carbide				79.08				10.79	3.85	93.72
5A11	-----do-----				79.82				9.55	4.24	93.61 ^a
6C3	85-percent silicon carbide, 15-percent boron carbide				14.36	59.89			22.21	3.02	99.48
6C12	-----do-----				14.09	59.80			21.07	2.93	97.89
7A2	Zircon			48.80		15.86	33.98		.82	< .01	99.47
7A10	--do--			47.63		16.30	35.31		.12	< .01	99.37
8A2	Zirconia (stabilized)			73.14 ^b			25.43		.16	< .01	99.04
8A12	-----do-----			73.25 ^b			25.80		.01	none	99.06

^aWet analysis for boron and carbon only. Spectrographic analysis shows no metals present, which indicates that deficiency is oxygen or nitrogen.

^bIncludes calcium content.



TABLE III - SHORT-TIME TENSILE STRENGTH OF SEVEN HOT-PRESSED CERAMICS

Specimen	Composition	Soaking temperature (° F)	Soaking time (hr)	Short-time tensile strength, (lb/sq in.)		Location of fracture	Surface of fracture (a)	Remarks
				1800° F	2200° F			
2A1	Magnesium oxide	1900	12	3,100	-----	Conical section	Smooth	
2A2	-----da-----	1900	12	3,100	-----	---da--	--da--	
2A3	-----da-----	----	----	-----	-----	---da--	--da--	Failed at room temperature, 2400 lb/sq in.
3A1	Titanium carbide	1900	13 $\frac{1}{2}$	15,850	-----	Gage length	Partly rough	
3A2	-----do-----	2300	----	-----	9,400	--da--	Rough	Soaking time unknown.
3A3	-----da-----	2300	5	-----	8,000	Edge of radius	-da--	
3A5	-----do-----	1900	4	17,200	-----	--da--	Partly rough	Flaw in specimen.
4A7	Zirconium carbide	1900	13	11,700	-----	Gage length	--da--	Flaw in specimen.
4A10	-----do-----	2300	4	-----	15,850	--da--	--	Fractured surface oxidized.
4A8	-----do-----	1900	4	14,450	-----	--da--	--	Fractured surface oxidized.
5A1	Boron carbide	1900	13 $\frac{1}{2}$	22,550	-----	--da--	Rough	Oxide film could not effectively be removed.
6C1	85-percent silicon carbide, 15-percent boron carbide	1900	16 $\frac{1}{2}$	9,950	-----	Radius	-da--	
6C3	-----da-----	2300	4	-----	7,100	--da--	-da--	Diaphragm of machine broke; on second run specimen broke at 4000 lb/sq in.
7A1	Zircon	1900	13 $\frac{1}{2}$	8,700	-----	Gage length	Partly rough	
7A3	--da--	2300	4	-----	3,600	--da--	--da--	
7A4	--da--	1900	4	6,200	-----	--da--	--da--	
7A5	--da--	2300	4	-----	2,350	--da--	--da--	
8A1	Zirconia (stabilized)	1900	12	5,250	-----	--da--	--da--	
8A3	-----da-----	1900	4	6,750	-----	--da--	Rough	

^aSmooth surface is 0 to 50 percent granular.
Partly rough is 50 to 90 percent granular.
Rough is 90 to 100 percent granular.



TABLE IV - THERMAL-SHOCK EVALUATION OF CERAMICS

Specimen	Composition	Number of cycles before failure			
		1800° F	2000° F	2200° F	2400° F
3A7	Titanium carbide	25	25	25	14
3A12	-----do-----	25	25	25	21
6C7	85-percent silicon carbide, 15-percent boron carbide	25	25	2	--
6C12	-----do-----	25	6	--	--
4A5	Zirconium carbide	22 ^a	--	--	--
7A10	Zircon	1	--	--	--
7A11	--do--	$\frac{1}{2}$	--	--	--
5A11	Boron carbide	$\frac{1}{2}$	--	--	--
5A12	-----do-----	$\frac{1}{2}$	--	--	--
2A7	Magnesium oxide	$\frac{1}{2}$	--	--	--
8A11	Zirconia (stabilized)	0	--	--	--
8A12	-----do-----	0	--	--	--

^aExcessive oxidation, sample fell out of holder.



TABLE V - COEFFICIENT OF LINEAR EXPANSION OF SEVEN
HOT-PRESSED CERAMICS

Material	Coefficient (in./in.)(°F) x 10 ⁻⁶	Temperature range (°F)
Titanium carbide	4.12	75-1100
Zirconium carbide	3.74	75-1000
Boron carbide	2.61	75-1100
85-percent silicon carbide, 15-percent boron carbide	2.34	75-1100
Magnesium oxide	6.94	75-1000
Zirconia (stabilized)	4.95	75-1100
Zircon	2.24	75-1100



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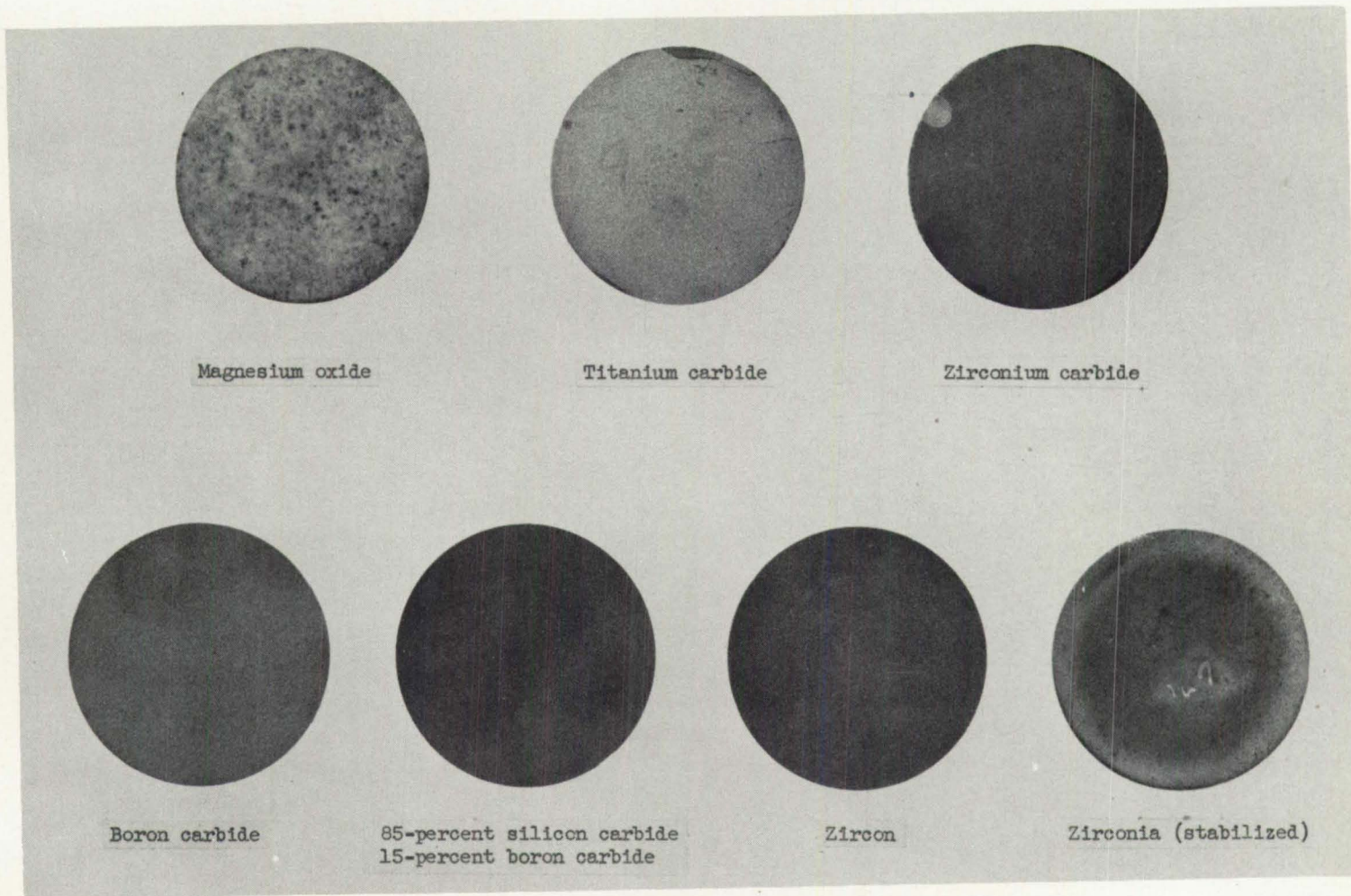


Figure 1. - Thermal-shock specimens before test.



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Figure 2. - Titanium-carbide specimen etched with potassium hydroxide plus potassium ferricyanide x 1500.

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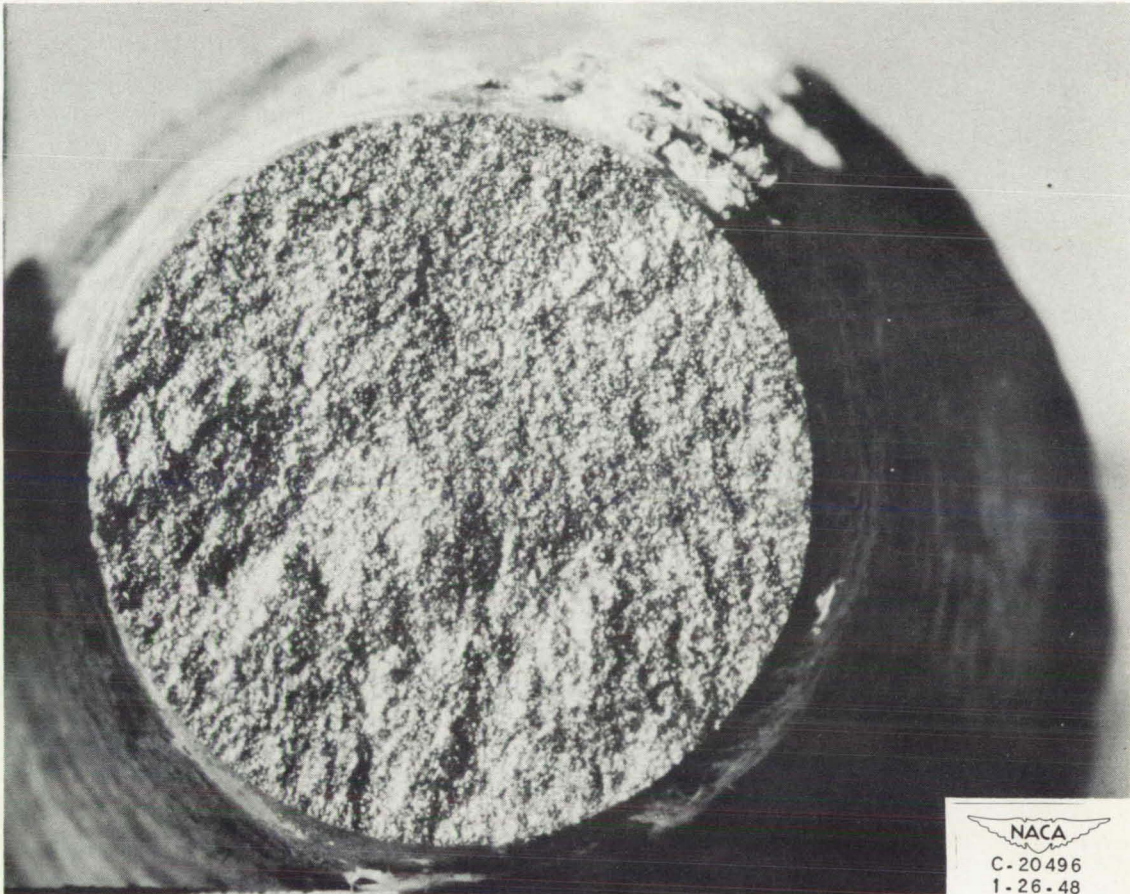


Figure 3. - Fractured surface of silicon carbide plus boron-carbide composition showing good break.

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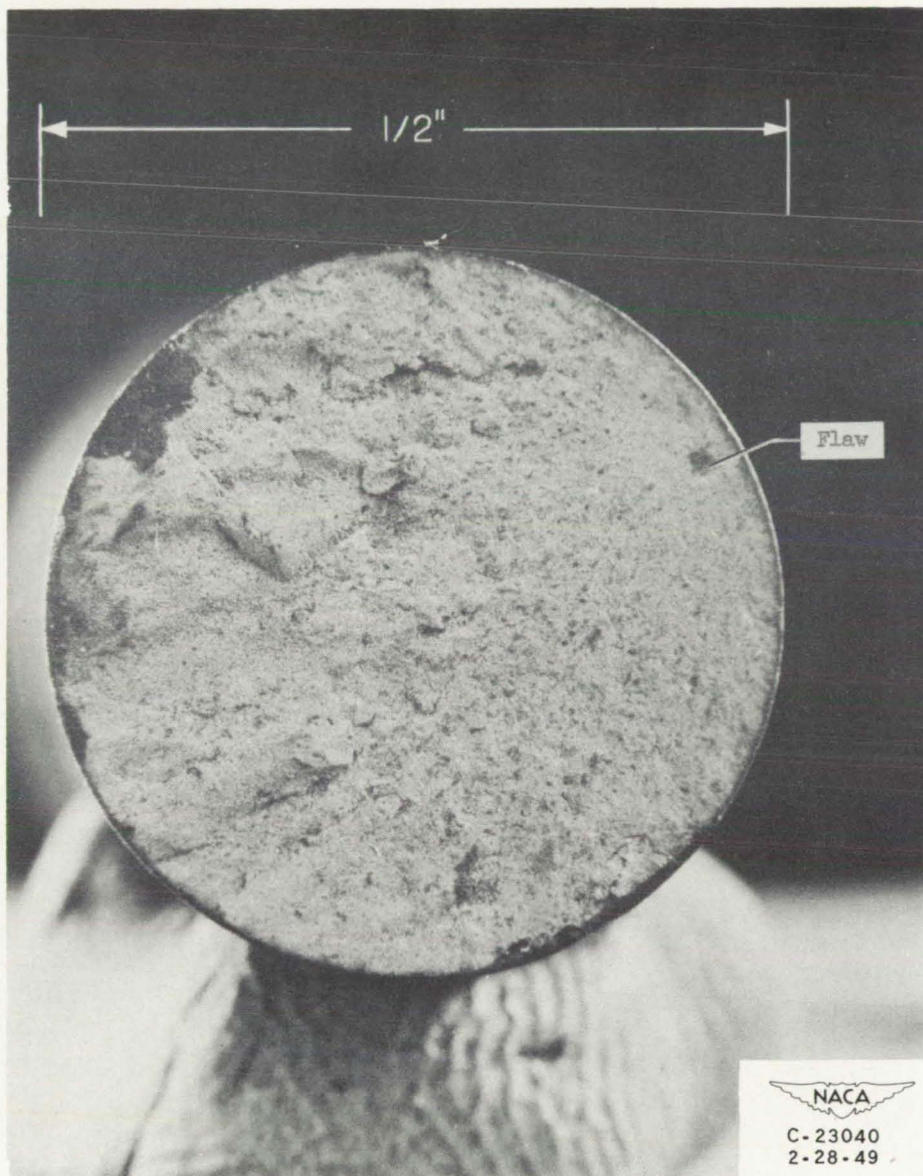


Figure 4. - Effect of flaw on surface of fracture of zirconium carbide.

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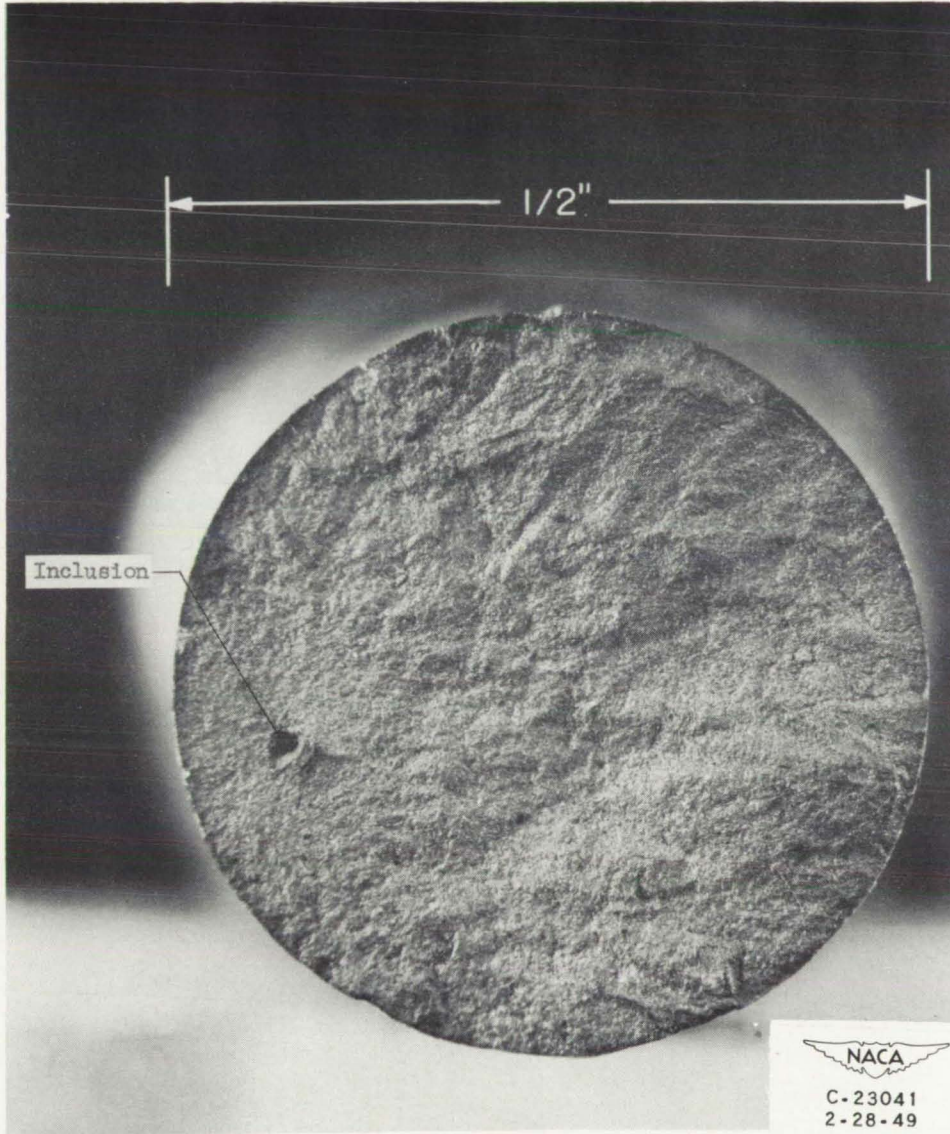
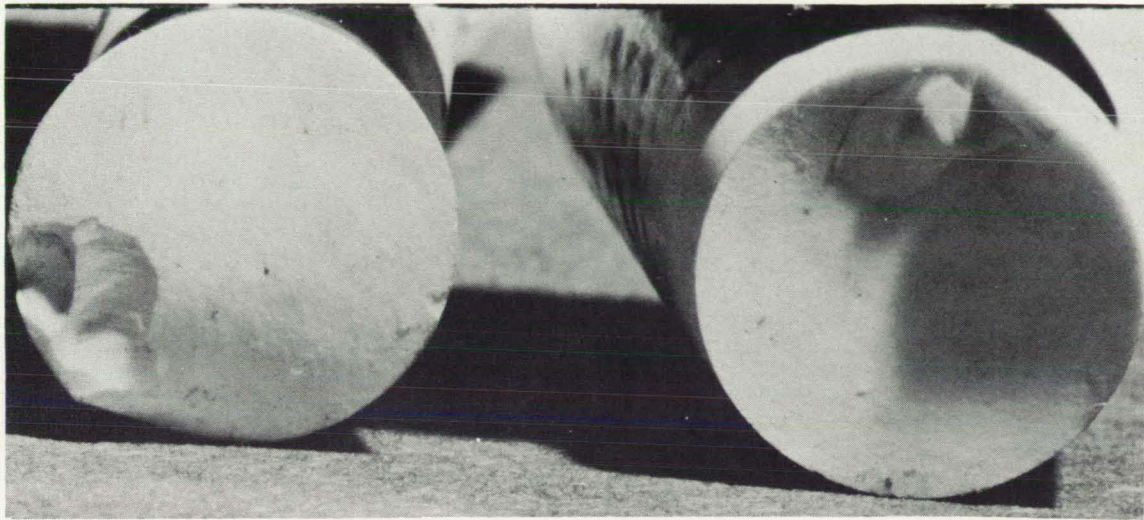


Figure 5. - Effect of inclusion on surface of fracture of titanium carbide.

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Figure 6. - Magnesium-oxide tensile specimen after test showing smooth conchoidal fracture.

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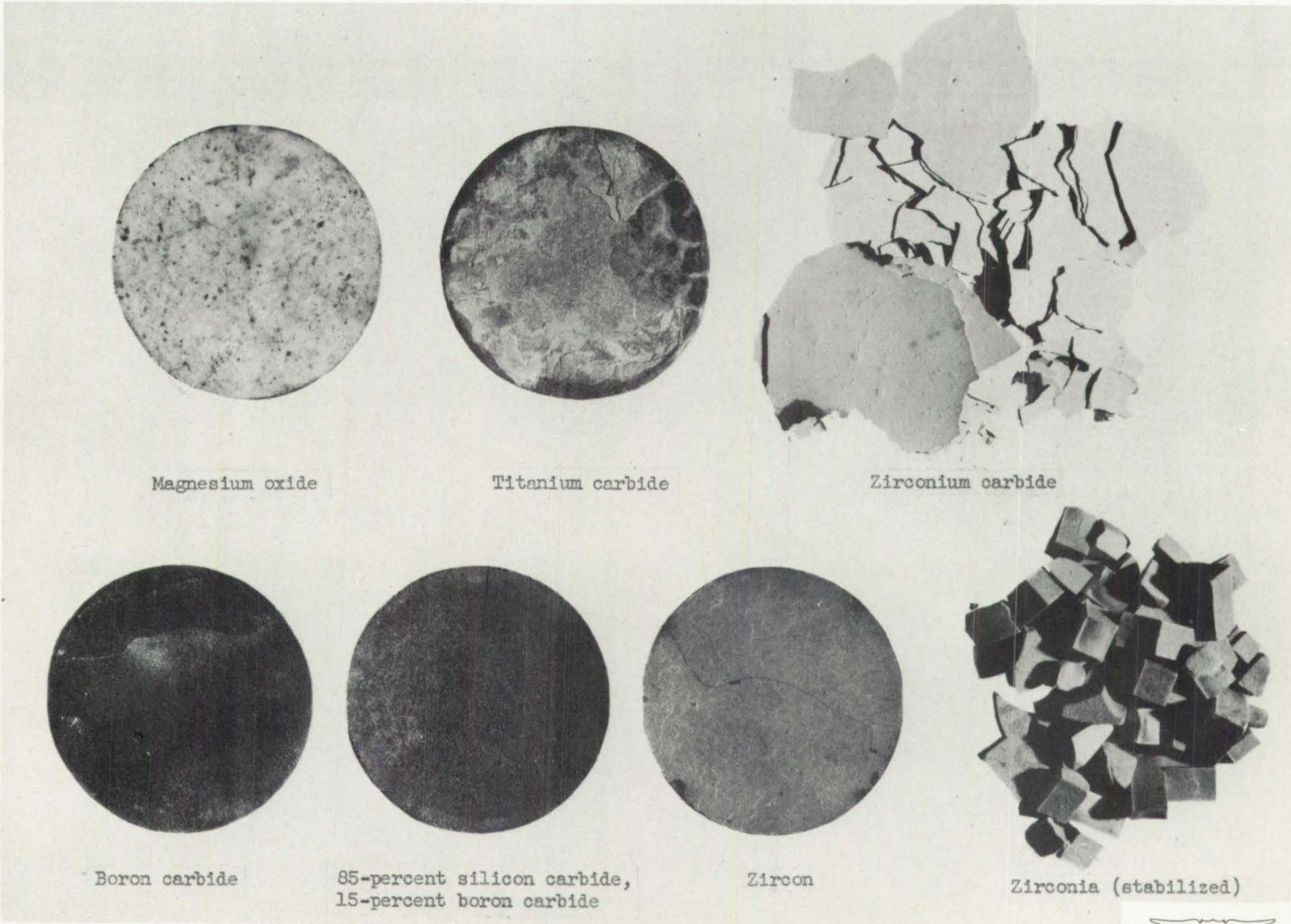


Figure 7. - Thermal-shock specimens after test.

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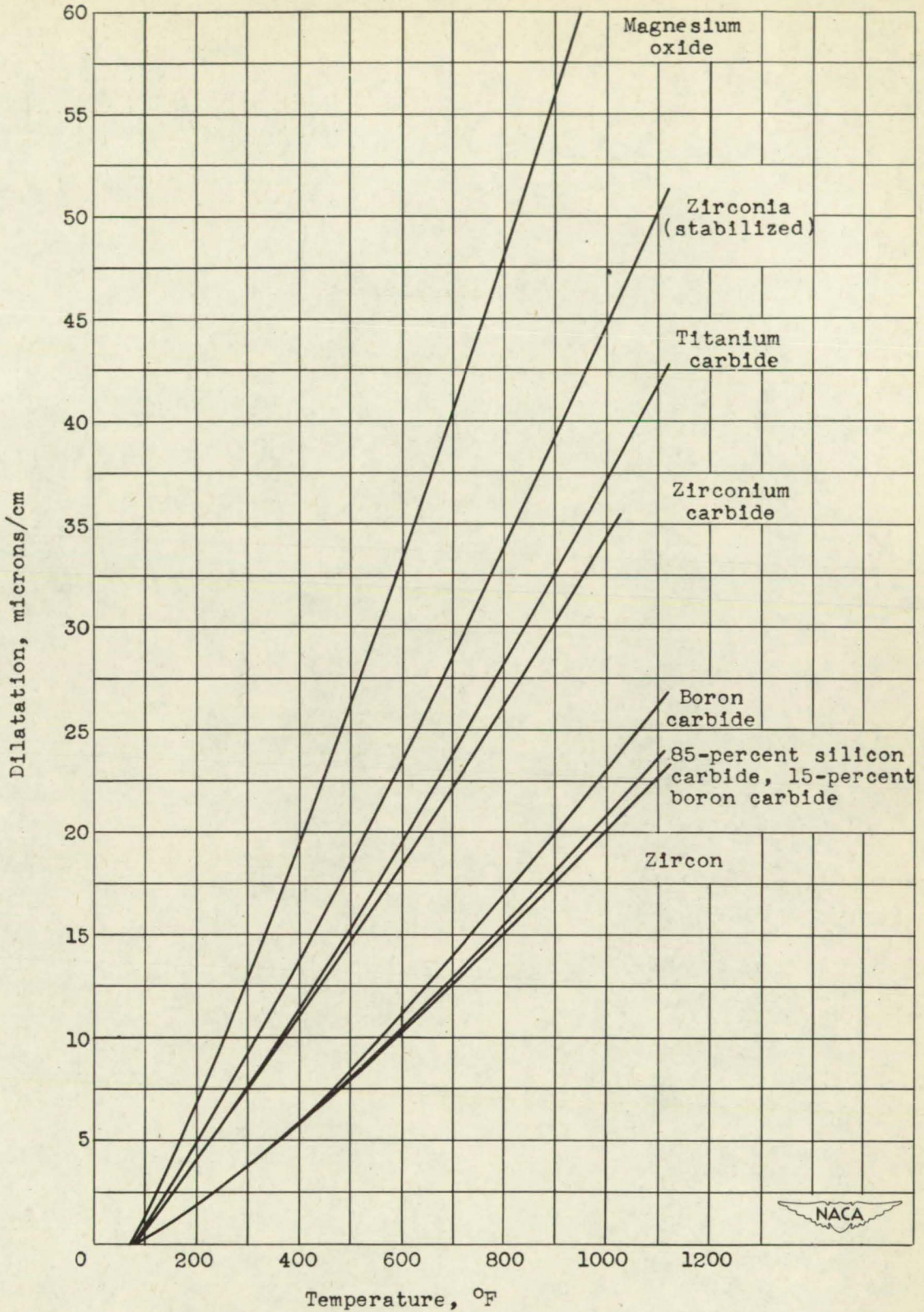


Figure 8. - Thermal-expansion characteristics of seven hot-pressed ceramics.