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Compilation of Information on Commercially Available Ceramic Coatings for High-Temperature Applications

J. I. Federer
A. J. Moorhead

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COMPILATION OF INFORMATION ON COMMERCIALLY AVAILABLE CERAMIC COATINGS FOR HIGH-TEMPERATURE APPLICATIONS

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J. I. Federer and A. J. Moorhead

ABSTRACT

Ceramic recuperator materials are exposed to high temperature corrosive/fouling flue gases during service. Recent exposure tests have shown that SiC ceramics are susceptible to corrosion in certain furnace environments. Ceramic coatings might protect SiC ceramics and other recuperator materials from corrosion. This compilation presents commercially available ceramic coatings that could be considered for corrosion protection of heat exchanger materials. The coatings include compositions based on alumina, alumina-magnesia, chromia, hafnia, silica, silicon carbide, titania, and zirconia. Recommendations for a program to evaluate and compare coatings are also presented.

INTRODUCTION

Several U.S. Department of Energy contractors have selected SiC ceramics as primary heat exchanger materials in high-temperature burner-duct recuperator (HTBDR) systems. These materials were selected on the basis of satisfactory properties at high temperatures including strength, oxidation resistance, thermal conductivity, and thermal shock behavior. In addition, tubes of required sizes were commercially available. Oxide ceramics, such as alumina and mullite, also have satisfactory strength and oxidation resistance for heat exchanger applications, but lack resistance to thermal shock.

Babcock & Wilcox Company selected siliconized SiC for the tubes in direct contact with high-temperature flue gases from a steel soaking pit.[1] AiResearch Manufacturing Company selected sintered-alpha SiC for a similar application.[2] As part of the HTBDR projects, the contractors and ORNL conducted exposure tests of SiC ceramics in steel reheat furnaces, steel

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soaking pits, and aluminum remelt furnaces. The purpose of these exposure tests was to assess the corrosion behavior of SiC ceramics in the combustion environments of furnaces that typically would use HTBDR systems.[3] Materials in these tests included two high-density sintered SiC ceramics, low-density recrystallized SiC (both bare and coated with CVD SiC), a siliconized SiC, two reaction sintered SiC ceramics, two Si_3N_4-bonded SiC ceramics, and two oxide ceramics. These materials represented the domestic commercially available SiC ceramics that might be used as recuperator tubes or structural components. Exposure temperatures ranged from 925 to 1250°C for 530 to 5545 h. All of the furnaces were fired with natural gas, but the amount of ash, slag, or process carryover varied considerably among the furnaces.

Significant corrosion occurred in SiC ceramic specimens installed in aluminum remelt furnaces and one of the steel soaking pits, the latter environment being particularly severe in terms of high temperature and amount and velocity of molten slag.[3] Projected surface recessions were 0.1 to 0.6 mm/y for materials exposed for 5545 h in an aluminum remelt furnace, but were in the range 3.5 to 6.8 mm/y for materials in the previously mentioned severe environment in a steel soaking pit. The lowest corrosion rates occurred in the high-density sintered SiC ceramics. The Si_3N_4-bonded SiC ceramics corroded at the highest rate, while siliconized and reaction-sintered materials corroded at rates intermediate to the other materials. The two oxide ceramics, alumina and mullite, which were included in one of the aluminum remelt furnaces, were relatively unaffected by that exposure.

Other compatibility tests, in addition to those conducted for the HTBDR projects, have also shown that SiC ceramics corrode in various industrial environments. An exposure of 4300 h in an aluminum remelt furnace resulted in a projected recession rate of ~0.5 mm/y for SiC ceramics.[4] Alumina, on the other hand, was essentially unaffected, while mullite corroded at a rate that projected to 0.2 mm/y.

In another exposure test of SiC ceramics in an aluminum remelt furnace, projected corrosion rates were about an order of magnitude higher

than those mentioned above [5] possibly due to higher temperatures and higher concentrations of corroding species in the flue gases. Apparently the halide-containing flue gases in aluminum remelt furnaces are particularly corrosive to SiC ceramics. Our recent laboratory studies using simulated industrial furnace atmospheres showed that NaCl and NaF, commonly found in aluminum remelt furnace exhausts, cause significant corrosion in sintered SiC, siliconized SiC, and reaction-sintered SiC at 1200°C. [6] Still other studies have shown that SiC ceramics are severely attacked by basic coal ash [7] and by flue gases from a glass furnace. [8]

These results have shown that SiC ceramics are susceptible to corrosion by certain industrial furnace environments. In two of these exposure tests, however, oxide ceramics were relatively unaffected when compared to the SiC ceramics. This observation led to consideration of using oxide ceramic coatings to protect SiC ceramics from corrosion.

A recent assessment of ceramic coatings for uncooled diesel engine applications emphasized zirconia coatings because of the desirable low thermal conductivity of zirconia. [9] Also discussed were various coating methods such as chemical vapor deposition, plasma spraying, and sol-gel coating. The assessment concluded that coatings can be produced to achieve certain desirable properties and that coatings are economically feasible for heat-engine applications. While zirconia coatings might protect SiC ceramics from corrosion in furnace environments, other types of coatings might also be useful. The purpose of the present study was to identify commercially available ceramic coatings (mostly oxides) for evaluation in exposure tests in industrial furnaces or in synthetic combustion atmospheres in the laboratory.

There are several technical considerations in the use of coatings for SiC ceramics including coating-substrate compatibility, adherence, and corrosion resistance. Although extremely important, the technical aspects of coatings are not treated in depth in this document. Instead, this study concentrated on determining the availability of ceramic coatings. This document brings various types of ceramic coatings to the attention of workers in the field of waste-heat recuperation and similar applications requiring materials with high-temperature corrosion resistance.

INFORMATION SOURCES

The initial search for information on oxide ceramic coatings involved a computer-conducted survey of several technical literature databases. This survey revealed numerous citations for non-metallic coatings. The Metals Abstracts Database, for example, yielded 230 citations for the period 1966 to 1982 related to non-metallic coatings for the protection of materials exposed to high temperature environments. Other data-bases yielded similar numbers of abstracts. A review of these abstracts revealed that many described refractory metal carbides, methods of evaluating coatings, methods of applying coatings, and compatibility of coatings with various substrates and environments. This information no doubt can be useful in selection of coatings for specific applications and in interpreting the behavior of coatings in service. However, because the main purpose of the present review was the identification of commercially-available oxide ceramic coatings that might be applicable for protection of SiC ceramics in industrial furnaces, we contacted industrial suppliers directly for information regarding their coatings.

Approximately 120 suppliers were identified in the company directory issue of *Ceramic Bulletin*.[10] Ten other suppliers were known from previous technical contacts. These potential suppliers (Appendix A) were sent letters explaining our interest and brief questionnaires requesting information on ceramic coatings (Appendix B). We received 42 replies to the survey, of which 26 were considered to be positive replies. The other 16 responders did not supply coatings of interest. The full addresses of the 26 responders who supplied information for this study are presented in Appendix C.

For this survey we were particularly interested in the following aspects of ceramic coatings:

- composition,
- maximum use temperature,
- method of application,
- physical properties,
- cost of application, and
- compatibility with industrial furnace environments.

Almost all 26 suppliers provided information on the first three items, some provied physical properties, but only a few provided cost or compatibility data. Lack of appropriate information indicates that several coatings should be selected for evaluation of properties, compatibility with SiC substrates, and corrosion behavior in both laboratory and industrial furnace environments.

COMPILATION OF COATING INFORMATION

Coatings types, compositions, other information, and suppliers are presented in Tables 1–6. The coatings are grouped according to the major chemical species, for example, alumina-base coatings. The information in these tables was provided by the coating suppliers in their literature or in the questionnaire. Specific information was not always supplied, hence the frequent blank spaces in the tables.

The only criterion for inclusion in this compilation of coatings was a use temperature of at least 1200°C. In the present context the use temperature refers to melting or decomposition temperatures. This property only indicates the potential service capability of a coating exposed to corrosive/fouling flue gases and particulates at temperatures up to approximately 1600°C. Melting might not render a coating ineffective in protecting a substrate. A sticky molten coating, however, might collect flue gas particulates, and would probably provide a better medium for transport of corrodents to the substrate than would a solid material. The ability of a coating to exist without decomposing, of course, is a basic requirement. This compilation, therefore, does not include coatings with melting or decomposition temperatures below 1200°C.

Information was obtained on six different types of coatings, some with numerous compositional variations. The types and number of coatings are:

- alumina-base (52),
- alumina magnesia (7),
- chromia-base (12),
- silica-base (22),
- titania-base (7), and
- zirconia-base (30).

Table 1. Alumina-base coatings

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	Al_2O_3	Other				
Ceramadip 538	major		1760 (3200)	25	dip, brush	Aremco Products, Inc.
Unikote S	88	12 SiO_2	1540 (2800)	~6	air spray, brush	Babcock & Wilcox
Unikote M	66	22 SiO_2 8 SiC	1370 (2500)		air spray, brush	Babcock & Wilcox
Jade Set Super	84	8 Cr_2O_3 6 P_2O_5	m.p. 1870 (3400)			E. J. Bartells Co.
Aluminum Oxide					plasma spray	Bay State Abrasives
PP-33	99.5		m.p. 2050 (3722)			
PP-34	99.5		m.p. 2050 (3722)			
PP-35	99.0		m.p. 2050 (3722)			
Alumina/ Titania					plasma spray	Bay State Abrasives
PP-32	97.5	2.5 TiO_2	m.p. 1790 (3250)			
PP-37	97.5	2.5 TiO_2				
PP-47	87	13 TiO_2				
PP-48	60	40 TiO_2	m.p. 1850 (3360)			
PP-31	50	50 TiO_2	m.p. 1850 (3360)			
Alfrax 17A[a]	major		1815 (3300)		brush, dip	Christy Firebrick Co.
Morcoset AC[b]	81	9 Cr_2O_3 3 P_2O_5 1 SiO_2	1815 (3300)		brush, dip	Christy Firebrick Co.
Duralco 903 Green	major		2065 (3750)	7	brush, trowel, air spray	Cotronics Corp.

Table 1. (continued)

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	Al_2O_3	Other				
Shamrock 391	67.5	2.5 SiO_2	1760 (3200)		air spray, brush	Didier Taylor Refractories
Resitect 180K Spezial	86.5	9.5 P_2O_5 3.0 SiO_2	1800 (3270)	8	brush, trowel	Didier-Werke AG
Kemort	48	43 SiO_2	1595 (2900)		dip, trowel	Gunning Refractories, Inc.
Super Kemort	50	45 SiO_2	1595 (2900)		dip, trowel	Gunning Refractories, Inc.
Aluminum Oxide					flame spray	Metallizing Co. of America, Inc.
KR98ZA	99					
KR98ZB	97	2 TiO_2				
KR94ZA	93	6 SiO_2				
Grey Alumina					plasma spray	Metco, Inc.
101	94	2 SiO_2 2.5 TiO_2				
101NS	94	2 SiO_2 2.5 TiO_2				
101B-NS	94	2 SiO_2 2.5 TiO_2				
101FP	97	3 TiO_2				
101SF	96	2 TiO_2				
White Alumina					plasma spray	Metco, Inc.
105	98.5	1 SiO_2				
105NS	98.5	1 SiO_2				
105NS-1	98.5	1 SiO_2				

Table 1. (continued)

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	Al_2O_3	Other				
Aluminum Oxide					plasma spray	Metco, Inc.
105SF	98.0	0.5 SiO_2				
105SFP	99.5					
Aluminum Oxide-Titanium Oxide 110	50	50 TiO_2			plasma spray	Metco, Inc.
Alumina-Titania Composite					plasma spray	Metco, Inc.
130	bal.	13 TiO_2				
130F	bal.	13 TiO_2				
131VF	60	40 TiO_2				
Alumina					plasma spray	Metco, Inc.
A-99	98	2 SiO_2				
A-99-X	98	2 SiO_2				
Alumina-Titania					plasma spray	Metco, Inc.
AT-3	91	3 SiO_2 3 TiO_2				
AT-13	83-88	12-14 TiO_2				
AT-40	57-63	37-43 TiO_2				
Wash	major	SiO_2, ZrO2			brush	New Castle Refractories, Co.
Rokide A	98.6	0.6 SiO_2			flame spray	Norton Co.

Table 1. (continued)

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	Al_2O_3	Other				
Plistix 900	90		>1925 (3500)	5	brush, gun, trowel	Plibrico Co.
PC Sealer	major		>1650 (3000)		paint, dip, air spray	Rex Roto Corp.
SP 160	major		≥1650 (3000)		paint, dip, air spray	Rex Roto Corp.
Pyrolite Sealer	100		>1650 (3000)		paint, dip	Rex Roto Corp.
Al_2O_3	99.5		2050 (3720)	7	plasma spray	Sylvester & Co.
Al_2O_3/TiO_2	97.5	2.5 TiO_2	1790 (3255)	6	plasma spray	Sylvester & Co.
Al_2O_3/TiO_2	50	50 TiO_2	1850 (3360)	6	plasma spray	Sylvester & Co.
LA-2	>99				D-gun	Union Carbide
LA-7	60	40 TiO_2			D-gun	Union Carbide

[a]Product of Carborundum Co.

[b]Product of Missouri Refractories Co., Inc.

Table 2. Alumina-magnesia coatings

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	Al_2O_3	Other				
Magnesia Alumina Spinel PP-49	72	28 MgO	m.p. 2135 (3875)		plasma spray	Bay State Abrasives
MG64ZA	39	1.5 CaO 56.2 MgO 3 SiO_2			flame spray	Metallizing Company of America, Inc.
SP70ZA	69.5	0.5 CaO 26.6 MgO 3.2 SiO_2			flame spray	Metallizing Company of America, Inc.
SP70ZB	69.3	1.0 CaO 25.0 MgO 2.6 SiO_2 1.6 TiO_2			flame spray	Metallizing Company of America, Inc.
Spinel MA-75	64.5–77.5	21.5–32.5 MgO			plasma spray	Muscle Shoals Minerals
Rokide MA	66.8	0.7 CaO 29.5 MgO 2.9 SiO_2			flame spray	Norton, Co.
Spinel	72	28 MgO	m.p. 2135 (3875)	5	plasma spray	Sylvester & Co.

Table 3. Chromia-base coatings

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	Cr_2O_3	Other				
Chrome Oxide	95		1990 (3450)		plasma spray	Bay State Abrasives
Kramic SCA	major	Al_2O_3 SiO_2	m.p. >2000 (3632)	12	air spray, drain cast	Kaman Sciences Corp.
Kramic MLC	major	Al_2O_3 SiO_2	m.p. >2000 (3632)	12	air spray, drain cast	Kaman Sciences Corp.
Chrome Oxide					flame spray	Metallizing Company of America, Inc.
CR80ZA	76	15 Al_2O_3 3 MgO 4 SiO_2				
CR80ZB	82	9 Al_2O_3 3 MgO 5 SiO_2				
Chromium Oxide					plasma spray	Metco, Inc.
106	96	2 TiO_2				
106F	96	2 TiO_2				
Chromium Oxide-Titanium Dioxide 111	45	55 TiO_2			plasma spray	Metco, Inc.
Chromium Oxide-Silica Composite 136F	bal	5 SiO_2 3 TiO_2			plasma spray	Metco, Inc.

Table 3. (continued)

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	Cr_2O_3	Other				
Chrome Oxide CR-98	98				plasma spray	Muscle Shoals Minerals
Rokide C	82.9	3.2 Al_2O_3 3.0 MgO 8.4 SiO_2			flame spray	Norton, Co.
Cr_2O_3	95		1990 (3450)	4	plasma spray	Sylvester & Co.
LC-4	>99				plasma spray	Union Carbide
LC-19	70	30 Al_2O_3			plasma spray	Union Carbide

Table 4. Silica-base coatings

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	SiO_2	Other				
Ceramacoat 512	major		1370 (2500)	11	air spray, brush	Aremco Products, Inc.
Ceramacoat 593	major		1370 (2500)	11	air spray, brush	Aremco Products, Inc.
Type SBE	major	Al_2O_3	1205 (2200)		air spray	Ceramic Refractory Corp.
Griptite Grey S	83	9 Al_2O_3	1540 (2800)		dip, trowel	Gunning Refractories, Inc.
Griptite Grey	64	27 Al_2O_3	1540 (2800)		dip, trowel	Gunning Refractories, Inc.
Griptite Red	49	42 Al_2O_3	1650 (3000)		dip, trowel	Gunning Refractories, Inc.
Griptite Blue	51	40 Al_2O_3	1705 (3100)		dip, trowel	Gunning Refractories, Inc.
Seal Kote	97		1540 (2800)		air spray	Gunning Refractories, Inc.
Seal Kote B	89		1540 (2800)		air spray	Gunning Refractories, Inc.
Neo-glassceramic Glass-bonded Ceramic Slurry	major		2000 (3630)	8	dip, brush	Materials Science & Technology, Inc.
G-11 Glaze	major		1260 (2300)		brush	New Castle Refractories Co.
H Glaze	major		1425 (2600)		brush	New Castle Refractories Co.
Glaze	major	Al_2O_3 Cr_2O_3	1400 (2550)			Norton Co.

Table 4. (continued)

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	SiO_2	Other				
Plistix Super	63	33 Al_2O_3	1640 (2980)	3	brush, trowel, gun	Plibrico Co.
Plistix Ladle Coat	36	Graphite 40 Al_2O_3	>1650 (3000)	3	brush, trowel	Plibrico Co.
RX-36	major	CaO Al_2O_3	1540 (2800)[a]		brush, spray, dip	RX Chemical Company, Inc.
Insa-Lute Hi-Temp Cement No.7	major		1370 (2500)	11	air spray, dip, brush	Sauereisen Cements Co.
Electric Resistor Cement No. P-78	major	Al_2O_3	1425 (2600)		air spray, dip, brush	Sauereisen Cements Co.
Solaramic Abrasive Coating RC-1	major		2000 (3630)		air spray	Solar Turbines Inc.
Solaramic S/N 5A	major	Cr_2O_3	1205 (2200)	8	air spray	Solar Turbines Inc.

[a]Vitrification temperature.

Table 5. Zirconia-base coatings

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	ZrO_2	Other				
Zirconia					plasma spray	Bay State Abrasives
PP-42	93	5 CaO	m.p. 2690 (4874)			
PP-42B	93	5 CaO	m.p. 2690 (4874)			
Magnesium Zirconate PP-45	80	20 MgO	m.p. 2100 (3830)		plasma spray	Bay State Abrasives
Type C-10A	major		m.p. 2480 (4500)		air spray	Ceramic-Refractory Corp.
Type C-90S	major	Al_2O_3, SiO_2	m.p. 2065 (3750)		air spray	Ceramic-Refractory Corp.
Duralco 904	major		2205 (4000)	7		Cotronics Corp.
Zirconia Wash A	89	4 CaO 2 SiO_2	1900 (3452)		air spray, brush	Didier Taylor Refractories Corp.
Zircon Wash A	61	2 Al_2O_3 36 SiO_2	1705 (3100)		air spray, brush	Didier Taylor Refractories Corp.
Kramic AC	major	Al_2O_3			air spray	Kaman Sciences Corp.
Zirconium Oxide					flame spray	Metallizing Company of America, Inc.
ZR92ZA	91	6 CaO 2 SiO_2				
ZS67ZA	65	34 SiO_2				

Table 5. (continued)

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	ZrO_2	Other				
Zirconium Oxide					plasma spray	Metco, Inc.
201	93	5 CaO				
201 NS	93	5 CaO				
201 B-NS	93	5 CaO				
201 B-NS-1	92	8 CaO				
202 NS	80	20 Y_2O_3				
Magnesium Zirconate					plasma spray	Metco, Inc.
210	bal.	24 MgO				
210 NS	bal.	24 MgO				
Calcium Zirconate 211	bal.	31 CaO			plasma spray	Metco, Inc.
Magnesium Zirconate MZ-80	bal.	18-25 MgO			plasma spray	Muscle Shoals Minerals
Zirconia Calcia ZC-5	91.5	5 CaO			plasma spray	Muscle Shoals Minerals
Zirconia Yttria					plasma spray	Muscle Shoals Minerals
ZY-7	bal.	7 Y_2O_3				
ZY-8	bal.	8 Y_2O_3				
ZY-20	75	20 Y_2O_3				
Rokide Z	94.6	3.7 CaO			flame spray	Norton Co.

Table 5. (continued)

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	ZrO_2	Other				
Rokide ZS	64.1	33.2 SiO_2			flame spray	Norton Co.
Electrotemp Cement No.8	major	P_2O_5 SiO_2	1425 (2600)	5	air spray, dip, brush	Sauereisen Cements, Co.
Thermal Barrier	92	8 Y_2O_3	m.p. 2595 (4700)		plasma spray	Solar Turbines Incoporated
Ca Stabilized ZrO2	92-94	6-8 CaO	2690 (4875)	6	plasma spray	Sylvester & Company
MgO/ZrO_2	80	20 Mg	2100 (3810)		plasma spray	Sylvester & Company

Table 6. Titania-base coatings

Designation	Nominal Composition (wt %)		Melting or use temperature, °C (°F)	CTE, $10^{-6}C^{-1}$	Method of application	Manufacturer or supplier
	TiO_2	Other				
Titanium Dioxide PP-46	94-95		m.p. 1788 (3245)		plasma spray	Bay State Abrasives
Alumina/Titania PP-31	50	50 Al_2O_3	m.p. 1850 (3360)		plasma spray	Bay State Abrasives
Aluminum Oxide-Titanium Oxide 110	50	50 Al_2O_3			plasma spray	Metco Inc.
Titania T-99	97.5				plasma spray	Muscle Shoals Minerals
$CaTiO_3$	59	41 CaO	m.p. 1415 (2580)	12	plasma spray	Solar Turbines Incorporated
TiO_2	95		m.p. 1788 (3245)	5	plasma spray	Sylvester & Company
Al_2O_3/TiO_2[a]	50	50 Al_2O_3	1850 (3360)		plasma spray	Sylvester & Company

[a]Also shown in Table 1.

Two other coatings, not shown in Tables 1–6, are silicon carbide (San Fernando Laboratories) and hafnia (Ultramet). Coating of SiC with SiC for corrosion resistance makes sense only if the coating has better corrosion resistance than the substrate. According to the manufacturer the extremely fine-grained SiC prepared by chemical vapor deposition (CVD) has superior oxidation resistance to that of SiC fabricated by more conventional methods, and, therefore, might also have better corrosion resistance. The hafnia coating is prepared by CVD of HfC, which is subsequently oxidized.

Eleven application methods were mentioned by the manufacturers: dipping, drain casting, brushing, painting, air spraying, plasma spraying, flame spraying, gunning, troweling, D-gunning, and CVD. Some of these might be substantially equivalent to each other.

RECOMMENDATIONS FOR A COATINGS EVALUATION PROGRAM

An assessment of the relative abilities of the coatings in Tables 1–6 to protect SiC ceramics in high temperature combustion environments is outside the scope of this report. Performance of this task would require much more information on such critical factors as adherence during thermal cycling, compatibility with SiC during long times at elevated temperatures, and corrosion resistance. A close match between coefficient of thermal expansion (CTE) of coating and substrate would favor adherence, while a high resistance to thermal shock would allow the coating to maintain structural integrity during thermal cycling. Thermal shock resistance parameters are calculated from physical and mechanical properties of the material. In general, these properties are known for major species such as dense alumina and some compositional variations, but are not known for the numerous compositional variations with (probably) lower densities represented by the coatings in this report. A variety of coatings should be subjected, therefore, to an extensive evaluation to determine their suitability for protecting SiC. This evaluation should involve various examinations and tests intended to identify the most adherent and protective coatings. The program might include the following features:

- one SiC ceramic substrate material in the form of high density tubing;
- a specification for coating density, open porosity, coefficient of thermal expansion, and minimum use temperature;
- several compositional variations of coatings of each general type (alumina-base, chromia-base, etc.) shown in Tables 1–6 and other promising coatings such as CVD SiC and hafnia mentioned previously;
- comparison of different methods of application (if more than one method is available) in terms of compositional and thickness uniformity, microstructure, and density;
- determination of coating adherence and compositional stability during slow, controlled rate heating/cooling cycles;
- determination of coating adherence and structural integrity during a standard thermal shock test;
- determination of coating/substrate compatibility during extended high temperature heat treatments;
- determination of fracture strengths of uncoated, as-coated, and coated and heat treated substrates;
- corrosion testing in synthetic combustion atmospheres containing halides or other suspected corrodents followed by determination of fracture strengths; and
- corrosion testing in selected industrial furnace environments followed by determination of fracture strengths.

No doubt, other activities could be included in an investigation of coatings. For example, the economic aspects of variations in methods of applying coatings as well as the performance of coatings on other SiC ceramics or other ceramics could be evaluated. An investigation incorporating the above activities, however, should reveal the feasbility of using coatings on SiC ceramics for corrosion protection.

REFERENCES

1. *High-Temperature Burner-Duct-Recuperator System Evaulation, Annual Report: October 1981-September 1982*, LRC 5282, Babcock & Wilcox Company, Lynchburg, Va., January 1984.

2. M. Coombs, D. Kotchick and H. Strumpf, *High-Temperature Burner-Duct-Recuperator (HTBDR) Program: Annual Report, October 1981 through September 1982*, DOE/ID/12170, U.S. Department of Energy, Idaho Falls, Idaho, May 1983.

3. J. I. Federer, T. N. Tiegs, D. M. Kotchick and D. Petrak, *Analysis of Candidate Silicon Carbide Recuperator Materials Exposed to Industrial Furnace Environments*, ORNL/TM-9677, July 1985.

4. J. I. Federer and P. J. Jones, *Oxidation/Corrosion of Metallic and Ceramic Materials in an Aluminum Remelt Furnace*, ORNL/TM-9741, December 1985.

5. A. D. Russell, C. E. Smeltzer, and M. E. Ward, *Waste Heat Recuperation for Aluminum Furnaces*, GRI-81/0160, Solar Turbines Inc., San Diego, Calif., April 1983.

6. J. I. Federer, J M Robbins, P. J. Jones, and C. Hamby, *Corrosion of SiC Ceramics in Synthetic Combustion Atmospheres Containing Halides*, ORNL-6258, December 1985.

7. M. K. Ferber and V. J. Tennery, "Behavior of Tubular Ceramic Heat Exchanger Materials in Basic Coal Ash from Coal-Oil-Mixture Combustion," *Bull. Am. Ceram. Soc.* 63(7), 898–904 (1984).

8. G. W. Weber and V. J. Tennery, *Materials Analyses of Ceramics for Glass Furnace Recuperators*, ORNL/TM-6970, November 1979.

9. W. J. Lackey, D. P. Stinton, G. A. Cerny, L. L. Fehrenbacher, and A. C. Schaffhauser, *Ceramic Coatings for Heat Engine Materials - Status and Future Needs*, ORNL/TM-8959, December 1984.

10. *Ceram. Bull.* 64(1), January 1985.

Appendix A

Names and locations of potential coating suppliers who were contacted for information on ceramic coatings

Able Supply Co.
Able Refractory Products
Box 912
Houston, TX 77001

Acurex Corporation
Aerotherm Division
555 Clyde Avenue
Mt. View, CA 94039

AFC Corporation
5183 W. Western Reserve Road
Canfield, OH 44406

Airco Carbon
800-0 Theresia Street
St. Marys, PA 15857

Air Products & Chemicals, Inc.
Box 538
Allentown, PA 18105

Allegheny Sand, Inc.
31 Moffett Street
Box 13566
Pittsburgh, PA 15243

Allied Mineral Products, Inc.
2700 Scioto Pkwy.
Columbus, OH 43220

Alon Processing, Inc.
Grantham Street
Tarentum, PA 15084

Amtec Industries, Inc.
Box 40388
Cleveland, OH 44140

Aremco Products, Inc.
Box 429
Ossining, NY 10562

Armco, Inc.
Box 600
Middletown, OH 45043

Artech Corporation
2901 Telestar Ct.
Falls Church, VA 22042

Astro Met Associates, Inc.
9974 Springfield Pike
Cincinnati, OH 45215

Babcock & Wilcox Co.
Insulating Products Div.
Box 923
Augusta, GA 30903

Ball Corporation
345 S. High Street
Muncie, IN 47302

Bartells, E. J., Co.
Sub. of A.P. Green Refractories
Box 997
Renton, WA 98057

Bay State Abrasives
Div. of Dresser Industries, Inc.
12 Union Street
Westboro, MA 01581

Bell Aerospace Textron
Div. of Textron Inc.
Box One
Buffalo, NY 14240

Bognar and Co.
31 Moffett Street
Box 13566
Pittsburgh, PA 15243

Butler Refractories
Box 751
Butler, PA 160030751

California Metal Enameling Co.
6904 E. Slauson Avenue
Los Angeles, CA 90040

Canadian Refractories
Dresser Canada, Inc.
Box 1750, Sta. B
Montreal, Quebec
CANADA, H3B 3L3

Carb-Rite Co.
31 Moffett Street
Box 13566
Pittsburgh, PA 15243

CCH Scientific
Box 1617
Costa Mesa, CA 92628

Cedar Heights Clay Co.
Box 295
Oak Hill, OH 45656

Ceramic Coating Co.
Box 370
Newport, KY 41072

C-E Refractories
Div. of Combustion Engineering
Box 828
Valley Forge, PA 19482

Ceramic Finishing Co.
Box 498
State College, PA 16801

Cer-Met, Inc.
7841 N. Tryon Street
Charlotte, NC 28213

Ceramic Refractory Corporation
Rutledge Road
RD 1
Transfer, Pennsylvania 16154

Christy Firebrick Co.
3144 N. Broadway
St. Louis, MO 63147

Commonwealth Scientific Corp.
500 Pendleton Street
Alexandria, VA 22314

Coors Porcelain Company
600 Ninth Street
Golden, CO 80401

Corundite Refractories Company
Div. of Dixon Ticonderoga Co.
Box 416
Massillon, OH 44646

Cotronics Corporation
3379 Shore Pkwy.
Brooklyn, NY 11235

Delta Resin Refractories
6263 N. Teutonia
Milwaukee, WI 53209

Detrick, M.H., Co.
500 Park Blvd.
Itasca, IL 60143

Diamonite Products
Sub. W. R. Grace & Co.
453 W. McConkey Street
Shreve, OH 44676

Didier Refractories Corporation
7575 Trans Canada Hwy.
St. Laurent, Quebec
CANADA, H4T 1V6

Didier Taylor Refractories Corp.
Box 44040
Cincinnati, OH 45244

Donoho Clay Company
2700 Dooley Avenue
Box 843
Anniston, AL 36202

Dow Corning Corporation
Box 994
Midland, MI 48640

Dura Temp Corporation
1750 Eber Road, Box 368
Holland, OH 43528

Dynamit Nobel of America
Kay-Fries, Inc., Chemical Div.
Ten Link Drive
Rockleigh, NJ 07647

Eagle-Picher Industries, Inc.
Quapaw Ceramics Dept.
Box 798
Quapaw, OK 74363

Electro-Science Labs, Inc.
2211 Sherman Avenue, Box 596
Pennsauken, NJ 08110

Engelhard Corporation
Menlo Park, CN-40
Edison, NJ 08818

Ferro Corporation
One Erieview Plaza
Cleveland, OH 44114

Ferro Enameling Company
Box 2246
Oakland, CA 94621

Fiber Materials, Inc.
Biddeford Industrial Park
Biddeford, ME 04005

GCA/Vacuum Industries
Five Middlesex Avenue
Somerville, MA 02145

General Refractories Co.
225 City Line Avenue
Bala-Cynwyd, PA 19004

Goodyear Aerospace Corporation
1210 Massillon Road
Akron, OH 44315

Green, A. P., Refractories Co.
Sub. of U. S. Gypsum Co.
Green Blvd.
Mexico, MO 65265

GTE Lab, Inc.
One Stamford Forum
Stamford, CT 06904

Gunning Refractories, Inc.
Sub. of BMI, Inc.
Box 38
Pedro, OH 45659

Harbison-Walker Refractories
Div. Dresser Industries, Inc.
One Gateway Center
Pittsburgh, PA 15222

Heany Industries, Inc.
Industrial Ceramic Division
Box 38
Scottsville, NY 14546

Heraeus Cermalloy, Inc.
Union Hill Industrial Park
West Conshohocken, PA 19428

Hoeganaes Corporation
Sub. of Interlake, Inc.
River Road and Taylor Lane
Riverton, NJ 08077

Holden, A. F., Co.
2195 S. Milford Road
Milford, MI 48042

Hommel, O., Co.
Box 475
Pittsburgh, PA 15230

Hooker Chemicals & Plastics Corp.
Industrial Chemicals Group
Box 728
Niagara Falls, NY 14302

Hughes Aircraft Company
Corporate Marketing
200 N. Sepulveda Blvd.
El Segundo, CA 90245

Inland Enterprises, Inc.
10237 Berea Road
Cleveland, OH 44102

International Lead Zinc
Research Organization, Inc.
292 Madison Avenue
New York, NY 10017

Ipsen Ceramics
Div. of Ipsen Industries
325 John Street
Pecatonica, IL 61063

Jasper Stone Company
14575 Garden Road
Golden, CO 80401

Kaiser Refractories
Div. Kaiser Alum. & Chem. Corp.
300 Lakeside Drive
Oakland, CA 94643

Kaman Sciences Coporation
Ceramic Department
Box 7463
Colorado Springs, CO 80933

Lafarge Refractaires
99 Avenue Aristide Briand,
B.P.560
92542 Montrouge, Cedex, FRANCE

Lambertville Ceramic
& Mfg. Co., Inc.
Box 128
Lambertville, NJ 08530

Lava Crucible Refractories Co.
Box 278
Zelienople, PA 16063

Manville Building Materials Group
Box 5108-RF
Denver, CO 80217

Mat'ls Div. & Fab. Comp. Div.
Armco Aero. & Strat, Mat'ls. Gr.
840 Newport Ctr. Dr., Suite 260
Newport Beach, CA 92660

Materials Research Corp.
Rt. 303
Orangeburg, NY 10962

Materials-Science & Technology,
Inc.
398 Princeton Court
College Park-Ladson, SC 29465

McCormick, J. S., Co.
25th St. & A.V.R.R.
Pittsburgh, PA 15222

Metallizing Co. of America, Inc.
361 S. Hamilton Street
Sullivan, IL 61951

Metco, Inc.
1101 Prospect Avenue
Westbury, L.I., NY 11590

Midland Materials Research
P. O. Box 186
Midland, Michigan 48640

Missouri Refractories Co., Inc.
24 Allen Avenue
Webster Groves, MO 63119

M&T Chemicals, Inc.
Industrial Chemicals Div.
One Woodbridge Ctr.
Woodbridge, NJ 07095

Muscle Shoals Minerals Co.
Div. of Unicorn Industries
1202 E. Second St.
Muscle Shoals, AL 35661

Nalco Chemical Co.
2901 Butterfield Road
Oak Brook, IL 60521

National Beryllia Corporation
Greenwood Avenue
Haskell, NJ 07420

New Castle Refractories
Div. Dixon-Ticonderoga Co.
Box 471
New Castle, PA 16103

Nock & Son Co.
Box 40368
Cleveland, OH 44140

North State Pyrophyllite Co., Inc.
Sub. of Resco Products
Box 7247
Greensboro, NC 27407

Norton Co.
One New Bond Street
Worcester, MA 01606

Oakite Products, Inc.
50 Valley Road
Berkeley Heights, NJ 07922

OCLI/Optical Coating Lab, Inc.
Santa Rosa, CA 95407

Pell Industries, Inc.
3000 Hwy. 501, R.D. 4
Myrtle Beach, SC 29577

Pemco Products Group
Mobay Chemical Corporation
5601 Eastern Avenue
Baltimore, MD 21224

Plibrico Company
1840 N. Kingsbury
Chicago, IL 60614

Refractory Sales & Service Co., Inc.
Box 885
Bessemer, AL 35021

Remet Corporation
Box 278, Bleachery Place
Chadwicks, NY 13319

Renite Company
Box 19235
Columbus, OH 43219

Rex Roto Corporation
Box 980
Fowlerville, MI 48836

Riverside Refractories, Inc.
Box 1096
Pell City, AL 35125

Rocky Mountain Refractory Service, Inc.
Box 7386
Colorado Springs, CO 80933

RX Chemical Co., Inc.
Box 188
Lake Geneva, WI 53147

Salazar & Sons, Inc.
1506 Clinton Place
River Forest, IL 60305

San Fernando Laboratories
10258 Norris Avenue
Pacoima, California 91331

Sauereisen Cements Company
RIDC Industrial Park
Pittsburgh, PA 15238

SGL Industries, Inc.
76 Euclid Avenue
Haddonfield, NJ 08033

Smith, A. O., Corporation
Box 584
Milwaukee, WI 53201

Solar Turbines, Inc.
Sub. of Caterpillar Tractor Co.
Box 85376
San Diego, CA 921385376

Spectra-Mat, Inc.
1240 Hwy. 1
Watsonville, CA 95076

Stettner Technical Ceramics, Inc.
6135 Airways Blvd., Box 2194
Chattanooga, TN 37421

Steuler International Corporation
5060 Navarre Road, S.W.
Canton, OH 44706

Swindress Bond, Inc.
101 Fairview Avenue
Pittsburgh, PA 15238

Sylvester & Company
24700 Highpoint Road
Beachwood, OH 44122

TAFA, Inc.
Box 1157
Bow (Concord), NH 03301

Technology, Inc.
Industrial Products Div.
335 N. Griffin Street
Grand Haven, MI 49417

Turbine Components Corporation
Diffusion Coating Division
2 Commercial Street
Branford, Connecticut 06405

Ultramet
12173 Montague Street
Pacoima, California 91331

Union Carbide Corporation
Coatings Service
2611 Waterfront Pkwy, E. Dr.
Indianapolis, IN 46224

Unique Kilns Div.
HED Industries, Inc.
Box 246
Ringoes, NJ 08551

Union Mining Co. of
Allegany County, Inc.
31 Moffett Street, Box 13566
Pittsburgh, PA 15243

Vulcan Materials Co.
Metals Div.
Box 7588
Birmingham, AL 35235

Wahl Refractories, Inc.
Green Springs Rd., Box 430
Fremont, OH 43420

Wesco Refractories, Inc.
410 E. Magnolia
Fort Worth, TX 76104

Westinghouse Electric Corporation
Industrial Ceramics Plant
Porcelain Park, 333 W. Third Street
Derry, PA 15627

Williams & Wilson, Ltd.
4570 Sheppard Ave., E.
Scarborough, Ontario, CANADA M1S 4K2

Zero Refractories, Inc.
15333 Racho Road
Taylor, MI 48180

Z.Y.P. Coatings, Inc.
Box 208
Oak Ridge, TN 37831

Appendix B

Letter and questionnaire sent to potential suppliers of coating materials and services to obtain information on ceramic coating

OAK RIDGE NATIONAL LABORATORY
OPERATED BY MARTIN MARIETTA ENERGY SYSTEMS, INC.

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37831

March 18, 1985

Gentlemen:

The U.S. Department of Energy is sponsoring work by industrial contractors to develop high temperature ceramic recuperator systems for recovering waste heat from industrial furnaces. The ceramic recuperators typically transfer waste heat in flue gases to combustion air, which results in a higher flame temperature. The higher flame temperature, in turn, allows less fuel use per unit of product, thereby effectively conserving energy. These heat recovery systems are intended for use on many types of industrial furnaces, including those with corrosive/fouling flue gases.

We have observed significant corrosion of silicon carbide (SiC) recuperator tubes in steel soaking pit and aluminum remelt furnace environments. As a result we are investigating coatings that might improve the corrosion resistance of SiC tubes. Your company is listed in the Company Directory issue of Ceramic Bulletin, January 1985, as a supplier of coatings. We would like to know more about the coatings that your company sells. We intend to compile information on various coatings to aid in selecting the most suitable coatings for particular applications. This compilation will appear in an ORNL report scheduled for publication later this year. Although our present interest is in coatings for service at temperatures of 1000°C (1832°F) and higher, we would like to learn about your product even if you feel it does not have potential application for high temperature corrosion resistance.

I have enclosed a form that can be used to inform me about your company's coatings. The form is designed to minimize the amount of time required on your part, and still provide enough information to indicate the suitability of the coatings for the intended application. I realize that you might not wish to provide proprietary information. If, for example, the composition is proprietary, perhaps you could use a generic term such as oxide coating, stabilized zirconia, etc. I would greatly appreciate receiving any technical literature or brochures describing the coatings.

Thank you for your assistance.

Sincerely,

J. I. Federer
Ceramic Technology Group
Metals and Ceramics Division

JIF:fwb

Enclosure

OAK RIDGE NATIONAL LABORATORY
COATING SURVEY

Coating name			
Composition			
Method of application			
Properties: Density			
Porosity			
Hardness			
Melting point			
Coeff. therm. exp.			
Other			
Typical uses			
Cost of application per unit area			
Literature or brochure available?			
Person to contact for additional information (name and phone number)			

Please return this form to:

J. I. Federer
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, TN 37831
Telephone (615)574-5131

Appendix C

Names, addresses, and telephone numbers of coating suppliers responding to request for information on ceramic coatings

1. Aremco Products, Inc.
P.O. Box 429
Ossining, NY 10562
Telephone: (914)762-0685

2. Babcock & Wilcox
Insulating Products Division
P.O. Box 923
Augusta, GA 30903
Telephone: (404)796-4200

3. E. J. Bartells Co.
Subsidiary of A.P. Green
Refractories
P.O. Box 997
Renton, WA 98057
Telephone: (314)473-3517

4. Bay State Abrasives
Industrial Products Section
Westborough, MA 01581-0623
Telephone: (617)366-4431

5. Ceramic-Refractory Corporation
Rutledge Road
Transfer, PA 16154
Telephone: (412)646-2800

6. Christy Firebrick Company
3144 North Broadway
St. Louis, MO 63147
Telephone: (314)421-4780

7. Cotronics Corportaion
3379 Shore Parkway
Brooklyn, NY 11235
Telephone: (212)646-7996

8. Didier Taylor Refractories Corp.
P.O. Box 44040
Cincinnati, OH 45244
Telephone: (513)388-2100

9. Didier-Werke A.G.
Postfach 129469-Didierstr. 27
6200 Wiesbaden 12
West Germany

10. Gunning Refractories, Inc.
P.O. Box 267
South Webster, OH 45682
Telephone: (614)778-2222

11. Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, CO 80933
Telephone: (303)599-1500

12. Materials Science and
Technology Inc.
398 Princeton Court
Ladson, SC 29456
Telephone: (803)797-3731

13. Metallizing Company of
America, Inc.
321 S. Hamilton Street
Sullivan, IL 61951
Telephone (217)728-7321

14. Metco Inc.
1101 Prospect Avenue
Westbury, NY 11590
Telephone (516)334-1300

15. Muscle Shoals Minerals
1202 East Second Street
Muscle Shoals, AL 35661
Telephone: (205)381-6620

16. New Castle Refractories Co.
P.O. Box 471
New Castle, PA 16103
Telephone: (412)654-7711

17. Norton Company
1 New Bond Street
Worcester, MA 01606
Telephone: (617)853-1000

18. Plibrico Company
1800 Kingsbury Street
Chicago, IL 60614
Telephone: (312)549-7014

19. Rex Roto Corp.
P.O. Box 980
Fowlerville, MI 48836
Telephone: (517)223-3787

20. RX Chemical Company, Inc.
P.O. Box 188
Lake Geneva, WI 53147
Telephone: (414)248-3216

21. San Fernando Laboratories
    10258 Norris Avenue
    Pacoima, CA 91331
    Telephone: (818)899-7484

22. Sauereisen Cements Company
    160 Gamma Drive
    Pittsburgh, PA 15238
    Telephone: (412)963-0303

23. Solar Turbines Incorporated
    P.O. Box 85376
    San Diego, CA 92138-5376
    Telephone: (619)238-6731

24. Sylvester & Company
    24700 Highpoint Road
    Beachwood, OH 44122
    Telephone: (216)831-0880

25. Ultramet
    12173 Montague Street
    Pacoima, CA 91331
    Telephone: (818)899-0236

26. Union Carbide Corporation
    P.O. Box 24901
    Indianapolis, IN 46224
    Telephone: (317)299-1934

INTERNAL DISTRIBUTION

1–2. Central Research Library
3. Document Reference Section
4–5. Laboratory Records Department
6. Laboratory Records, ORNL RC
7. ORNL Patent Section
8. P. Angelini
9. S. Baik
10. P. F. Becher
11. A. Bleier
12. E. E. Bloom
13. R. A. Bradley
14. A. J. Caputo
15. R. S. Carlsmith
16. P. T. Carlson
17. J. A. Carpenter, Jr.
18. F. C. Chen
19. W. P. Eatherly
20–24. J. I. Federer
25. M. L. Grossbeck
26. H. S. Hsu
27. M. A. Janney
28. R. R. Judkins
29. M. P. Kertesz
30. M. B. Lewis
31. E. L. Long, Jr.
32. R. W. McClung
33. C. A. McHargue
34. J. W. Michel
35–39. A. J. Moorhead
40. M. Olszewski
41. J M Robbins
42. M. L. Santella
43. A. C. Schaffhauser
44. J. L. Scott
45. G. M. Slaughter
46. J. O. Stiegler
47. D. P. Stinton
48. V. J. Tennery
49–51. P. T. Thornton
52. T. N. Tiegs
53. J. R. Weir
54. R. J. Charles (Consultant)
55. G. Y. Chin (Consultant)
56. H. E. Cook (Consultant)
57. Alan Lawley (Consultant)
58. W. D. Nix (Consultant)
59. J. C. Williams (Consultant)

EXTERNAL DISTRIBUTION

60–61. AEROJET ENERGY CONVERSION COMPANY, P.O. Box 13222, Sacramento, CA 95813

L. Hoffman
H. W. Williams

62–63. AIRESEARCH MANUFACTURING COMPANY, 2525 W. 190th Street, Torrance, CA 90509

M. G. Coombs
D. M. Kotchick

64. AREMCO PRODUCTS, INC., P.O. Box 429, Ossining, NY 10562

M. J. Wandzilak

65–66. BABCOCK AND WILCOX, P.O. Box 239, Lynchburg, VA 24505

D. Petrak
J. E. Snyder

67. BABCOCK AND WILCOX, Insulating Products Division, P.O. Box 923, Augusta, GA 30923

T. R. Viverito

68. E. J. BARTELLS CO., Subsidiary of A. P. Green Refractories, P.O. Box 997, Renton, WA 98057

M. Schnake

69. BAY STATE ABRASIVES, Industrial Products Section, Westborough, MA 01581-0623

R. C. Pelletier

70. C&H COMBUSTION, 1104 E. Big Beaver Road, Troy, MI 48083

R. G. Graham

71. CABOT CORPORATION, 1020 West Park Avenue, Kokomo, IN 46901

M. F. Rothman

72. CERAMIC-REFRACTORY CORPORATION, Rutledge Road, Transfer, PA 16154

C. J. Knight

73. CHRISTY FIREBRICK COMPANY, 3144 North Broadway, St. Louis, MO 63147

R. Domst

74. COMBUSTION ENGINEERING, INC., 911 West Main Street, Chattanooga, TN 37402

C. H. Sump

75. CONSOLIDATED NATURAL GAS, 11001 Cedar Avenue, Cleveland, OH 44106

J. Bjerklie

76–78. COORS PORCELAIN COMPANY, 600 Ninth Street, Golden, CO 80401

C. Dobos
R. Kleiner
D. Roy

79. COTRONICS CORPORATION, 3379 Shore Parkway, Brooklyn, NY 11235

B. Resnick

80. DIDIER TAYLOR REFRACTORIES CORP., P.O. Box 44040, Cincinnati, OH 45244

D. G. Patel

81. DIDIER-WERKE A.G., Postfach 129469-Didierstr. 27, 6200 Wiesbaden 12, West Germany

Dr. Jeschke

82. GAS RESEARCH INSTITUTE, 8600 West Bryn Mawr Avenue, Chicago, IL 60631

W. W. Liang

83–84. GTE PRODUCTS CORPORATION, Hawes Street, Towanda, PA 18848

J. L. Ferri
J. Gonzalez

85. GUNNING REFRACTORIES, INC., P.O. Box 267, South Webster, OH 45682

R. V. Kilgore

86. HAGUE INTERNATIONAL, 3 Adams Street, South Portland, MA 04106

S. B. Young

87–88. IIT RESEARCH INSTITUTE, 10 West 35th Street, Chicago, IL 60616

J. W. Adams
D. C. Larsen

89. KAMAN SCIENCES CORPORATION, P.O. Box 7463, Colorado Springs, CO 80933

J. Schneider

90. MATERIALS SCIENCE AND TECHNOLOGY INC., 398 Princeton Court, Ladson, SC 29456

B. V. J. Rao

91. METALLIZING COMPANY OF AMERICA, INC., 321 S. Hamilton Street, Sullivan, IL 61951

J. Cook

92. METCO INC., 1101 Prospect Avenue, Westbury, NY 11590

V. J. Lanza

93. MUSCLE SHOALS MINERALS, 1202 East Second Street, Muscle Shoals, AL 35661

M. E. VandenBergh

94. NEW CASTLE REFRACTORIES COMPANY, P.O. Box 471, New Castle, PA 16103

P. J. Burke

95–97. NORTON COMPANY, Worcester, MA 01606

N. H. Burlingame
B. D. Foster
M. L. Torti

98. PENNSYLVANIA STATE UNIVERSITY, 201 Steidle Building, University Park, PA 16802

R. E. Tressler

99. PLIBRICO COMPANY, 1800 Kingsbury Street, Chicago, IL 60614

L. Krietz

100. REX ROTO CORPORATION, P.O. Box 980, Fowlerville, MI 48836

S. R. Schenck

101. RX CHEMICAL COMPANY, INC., P.O. Box 188, Lake Geneva, WI 53147

R. Newcomb

102. SAN FERNANDO LABORATORIES, 10258 Norris Avenue, Pacoima, CA 91331

E. S. Lillybeck

103. SAUERIESEN CEMENTS COMPANY, 160 Gamma Drive, Pittsburgh, PA 15238

G. R. Hall

104. SOHIO ENGINEERED MATERIALS COMPANY, Structural Ceramics Division, P.O. Box 10549, Niagara Falls, NY 14302

J. Halstead

105–108. SOLAR TURBINES INCORPORATED, P.O. Box 85376, San Diego, CA 92138-5376

T. A. Argabright
C. E. Smeltzer
A. R. Stetson
M. E. Ward

109. SYLVESTER & COMPANY, 24700 Highpoint Road, Beachwood, OH 44122

R. P. Vento

110–111. THERMO ELECTRON CORPORATION, P.O. Box 459, Waltham, MA 02254

W. E. Cole
R. DeSaro

112. ULTRAMET, 12173 Montague Street, Pacoima, CA 91331

R. H. Tuffias

113. UNION CARBIDE CORPORATION, P.O. Box 24901, Indianapolis, IN 46224

C. R. McKinsey

114. UNIVERSITY OF ILLINOIS AT CHAMPAIGN-URBANA, 105 W. Goodwin Avenue, Urbana, IL 61801

M. K. Ferber

115. UNIVERSITY OF ILLINOIS AT CHICAGO, P.O. Box 4348, Chicago, IL 60680

M. J. McNallan

116–118. DOE, IDAHO OPERATIONS OFFICE, 550 2nd Street, Idaho Falls, ID 83401

F. Childs
J. B. Patton
W. H. Thielbar

119–121. DOE, OFFICE OF INDUSTRIAL CONSERVATION, Forrestal Building, 1000 Independence Avenue, Washington, DC 20585

S. L. Richlen
J. R. Rossmeissl
W. B. Williams, Director

122. DOE, OAK RIDGE OPERATIONS OFFICE, P.O. Box E, Oak Ridge, TN 37831

Office of Assistant Manager for Energy Research and Development

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