

U. C. Lawrence Berkeley Laboratory
Library, Berkeley

LBL-37487

UC-404

ORNL/Sub94-SS109/01

FOR REFERENCE

Not to be taken from this room

**FEASIBILITY OF SYNTHESIZING OXIDE FILMS
ON CERAMIC AND METAL SUBSTRATES***

Final Report: August '94 through May '95

July 1995

Research sponsored by the U.S. Department of Energy,
Fossil Energy
Advanced Research and Technology Development Materials Program

Report prepared by
Ian G. Brown
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
under
Memo P.O. 10X-SS109V, WBS Element LBL-2

for

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC
for the
U.S. Department of Energy
under Contract No. DE-AC05-84OR21400

REFERENCE COPY
Does Not
Circulate

Bldg. 50 Library.

LBL-37487

Copy 1

*This work was supported by the U.S. Department of Energy, Office of Advanced Research, Fossil Energy, under Contract Number DE-AC03-76SF00098.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-37487
UC-404
ORNL/Sub94-SS109/01

FEASIBILITY OF SYNTHESIZING OXIDE FILMS
ON CERAMIC AND METAL SUBSTRATES*

Final Report: August '94 through May '95

July 1995

Report prepared by
Ian G. Brown
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

under

Memo P.O. 10X-SS109V, WBS Element LBL-2

for

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC
for the
U.S. Department of Energy
under Contract No. DE-AC05-84OR21400

*This work was supported by the U.S. Department of Energy, Office of Advanced Research, Fossil Energy, under Contract Number DE-AC03-76SF00098.

Feasibility of Synthesizing Oxide Films on Ceramic and Metal Substrates

Memo P.O. 10X-SS109V, WBS Element LBL-2

Principal Investigator: Ian Brown

Institution: Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Project Period: August '94 through May '95

Summary

We have carried out a preliminary exploratory program to investigate the feasibility of synthesizing highly-adherent alumina and chromia films on SiC and FeAl substrates using plasma-based methods. A magnetically-filtered, cathodic-arc-produced, metal plasma (Al or Cr) is deposited on the substrate in the presence of a low pressure gaseous oxygen background while the substrate is simultaneously repetitively pulse biased, providing a means of controlling the incident ion energy. In the early stages of the process the ion energy is held in the keV range so as to produce atomic mixing at the film-substrate interface (ion stitching), and in the latter stages of deposition the energy is reduced to ~200 eV (IBAD range) to provide a means of controlling the film structure and morphology. Near-stoichiometric films of alumina and chromia were formed on small SiC and FeAl substrates and characterized in a number of ways, including by RBS, X-ray diffraction, adhesion, and we also did some preliminary temperature cycling experiments. The alumina films were of thickness from 0.2 to 1.5 μ , amorphous prior to heat treatment, and showed an α -alumina phase after heat treating at 1000°C for up to 16 hours. The film substrate adhesion was typically greater than ~70 MPa prior to heating, and the thinner films maintained their adhesion even after repetitive cycling in temperature between ambient and 1000°C. We conclude that the plasma and ion beam techniques that we have developed provide important tools for the formation of highly adherent and thermally tolerant ceramic films.

Research sponsored by the U.S. Department of Energy, Fossil Energy Advanced Research and Technology Development Materials Program, DOE/FE AA 15 10 10 0, Work Breakdown Structure Element LBL-2

1. INTRODUCTION

Vacuum arc plasma discharges are intense sources of highly ionized, dense metal plasmas. Plasma generators based on this kind of discharge can be used to deposit thin films of various kinds including metals and alloys, and if the source is operated in a gaseous background then compounds including ceramic oxides can also be formed. We have developed techniques that combine plasma deposition with ion bombardment to create a powerful and adaptable new technology that is environmentally friendly, highly efficient, can be scaled up to large size, and can synthesize films of a range of materials¹⁻⁴. The films can be atomically mixed to the substrate by the ion bombardment phase of the process to produce excellent film/substrate bonding at the atomic level.

A metal plasma of the required species is formed by a vacuum arc plasma gun and directed toward the substrate with a moderate streaming energy, typically of order 100 eV. At the same time, the substrate is repetitively pulse biased to a moderate negative voltage (typically a few hundred to a few tens of kilovolts), thereby accelerating a fraction of the incident ion flux and energetically bombarding the ions into the substrate and the previously-deposited film. This technique provides a means for precise control of the energy of the depositing plasma ions. We use an early-time high ion energy so as to atomically mix the film into the substrate, and a lower (but optimized) ion energy during the bulk of the film growth so as to add an 'ion assist' to the deposition (similar to an ion beam assisted deposition, or IBAD, process). In this way the film is 'ion stitched' (ion bombardment formation of a graded interface) to the substrate and has very strong adhesion, and it is also of high density (void-free), good structure (eg, not columnar), and good morphology (eg, close to atomically smooth).

In the work described here we have used this plasma materials synthesis technique to form films of Al₂O₃ and Cr₂O₃ on SiC and FeAl substrates. The films have been characterized, both before and after 1000°C heat treating, for composition and phase using Rutherford backscattering spectrometry (RBS) and X-ray diffraction analysis, and the film-substrate adhesion has been measured using a Sebastian-type pull tester. In the following we firstly outline the plasma and ion beam processing set-up, the substrate preparation, and the characterization methods used. The experimental results of the program to-date are then presented. Finally, we summarize and comment on the suitability of the method for this field of application.

2. EXPERIMENTAL PROCEDURE

2.1 Plasma Processing

We have made a number of different kinds of vacuum arc plasma guns, from small pulsed versions to a large dc embodiment. The sources can be operated either in a repetitively pulsed mode with pulse duration between 50 μs and 5 ms, or with long pulses (tens or hundreds of milliseconds), or d.c.; arc current is typically in the range 100 – 250 A. The guns are UHV-compatible and the cryogenically-pumped system base pressure is typically about 1 x 10⁻⁶ Torr.

For the alumina and chromia films produced in this work, we used a “minigun” (Fig. 1) with arc pulses of 5 ms duration and at a repetition rate of about 1 pulse per second. The cathode is a central cylindrical rod of the desired metal plasma species surrounded coaxially by a cylindrical anode. The arc pulses are initiated by a short ($\sim 10 \mu\text{s}$) high voltage ($\sim 10 \text{ kV}$) trigger spark to the cathode. The plasma is created on the cathode surface and leaves the source as a directed plume through the annular anode. It is a fundamental characteristic of this kind of plasma discharge^{5,6} that along with the plasma formation, a small fraction of 'macroparticles' is also produced – small particles of metallic cathode debris of dimension in the range $0.1 - 10 \mu$. If macroparticle filtering is desired, as for the present purpose, a magnetic duct of suitable size is attached so that the plasma streams directly from the plasma gun into the filter⁷. With optimum magnetic field configuration^{8,9} and optimum bias of the filter wall, about 25% of the ions produced in the arc discharge can be transported through the filter. Figure 2 shows plasma flowing through the magnetic filters used in the present work. The overall plasma deposition system thus consists of the repetitively pulsed plasma gun in conjunction with the 90° bent magnetic filter. Plasma exits the filter and deposits onto the appropriately positioned substrate.

Films of metallic oxides can be formed simply by carrying out the plasma deposition not in a high vacuum environment, but in a somewhat higher pressure ambient of oxygen gas^{10,11}. We have found empirically that a pressure in the range 1 - 100 mTorr is suitable for most metal oxides. Here, the oxygen background pressure was 10 to 15 mTorr. The oxygen is both entrained in the plasma stream, ionized, and deposited in the plasma state, as well as reacting at the freshly-deposited metallic surface to form a metal oxide. The net result is that, for the optimal oxygen pressure, a stoichiometric oxide film is formed. In the work reported on here, we used mostly an aluminum plasma and so formed an alumina film. Some preliminary work was also done with chromium, and we could form good quality chromia films. In the following we report on that part of the work on which we have concentrated our effort to-date – the formation and properties of alumina films.

Ion energy of the depositing plasma flux is controlled by repetitively pulse biasing the substrate. Typically the pulse duration might be $\sim 10 \mu\text{s}$ and the duty cycle $\sim 10 - 50\%$. Pulsing of the bias voltage is necessary (for all but the lowest bias voltages) because a high voltage dc bias would cause an electrical discharge between the substrate and the vessel or the plasma gun; the plasma would be grossly perturbed (because the plasma sheath would expand from the substrate to large distances) and the ions would not be accelerated. The solution is to switch off the bias before such major perturbation can occur (to limit the sheath expansion to modest distances), let the plasma recover, and then repeat the process; ie, to do the biasing in a repetitively pulsed mode. For the early stages of the deposition process the pulse bias is held at a relatively high voltage of 2.2 kV. The mean aluminum ion energy is then 3.75 keV, because the mean ion charge state of the aluminum plasma is 1.7 (ref. 12) and $E_i = QV$. This energy results in implantation into the substrate to a depth of up to $\sim 100 \text{ \AA}$ and intermixing of the Al film that is deposited during the pulse-off part of the pulse biasing. The aluminum film thus grows on the SiC substrate from a highly mixed interface. When an oxide is to be formed, the oxygen is also intermixed both by direct implantation of ionized oxygen as well as by recoil implantation of oxygen in the surface film. When a film thickness of just a few tens of angstroms has

accumulated, the pulse bias voltage is reduced, since intermixing with the substrate is no longer a factor and the higher ion energy would sputter away the already-deposited film. Moreover, it is known from a large body of work on ion assisted deposition that a modest ion energy can be highly advantageous for controlling such characteristics as the density, morphology and structure of the film. For the bulk of the plasma deposition process the pulse amplitude is kept at 200 V.

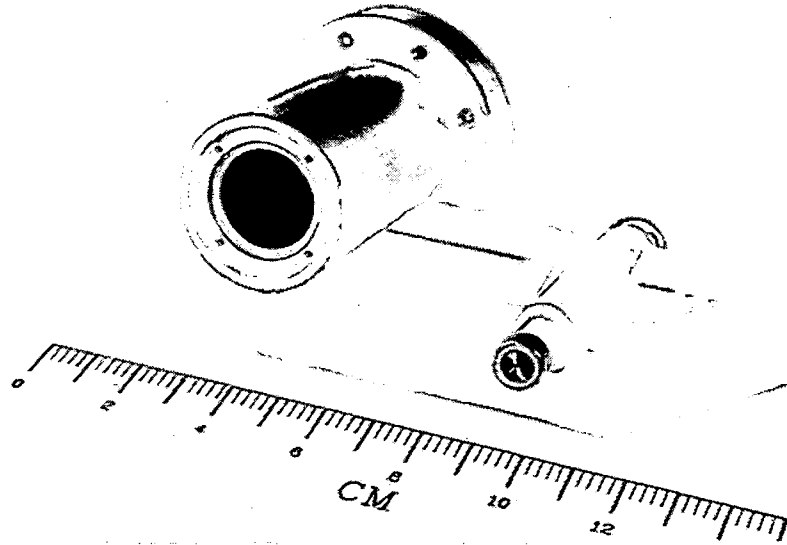


Figure 1. Partially disassembled vacuum arc plasma gun of the kind used here. The cathode assembly is shown removed from the anode. (CBB928-6317)

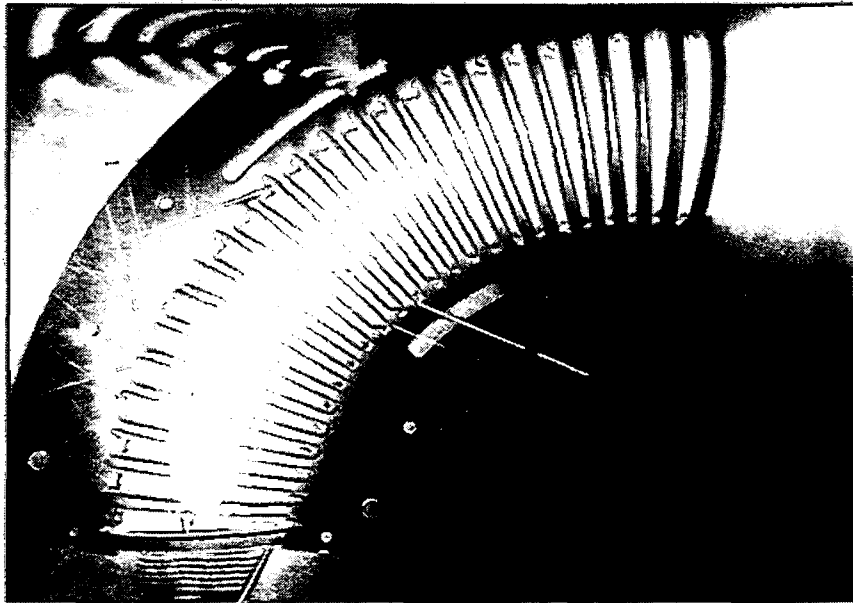


Figure 2. Magnetic filter, showing plasma injected from the gun at the lower left streaming through it and exiting at the upper right. (CBB933-1253)

2.2 Substrate Preparation

The substrates were small coupons of silicon carbide and iron aluminide. The SiC was CVD-produced and was purchased from Morton Advanced Materials; the polished coupons were 0.5" x 0.5" square and 0.1" thick. The FeAl material was supplied by ORNL and was in the form of polished 1 cm x 2 cm coupons approx. 1 mm thick. We used that specific iron aluminide known as FAL and having composition Fe - 26%Al - 5%Cr - 0.1%Zr - 0.05%B (atomic percentages).

2.3 Characterization

Analysis of film composition was done with Rutherford backscattering spectrometry (RBS) using 1.8 MeV He⁺ ions, and X-Ray diffraction analysis was used to determine the crystallographic phase. Film adhesion was measured with a Sebastian-type pull tester using Sebastian studs epoxied to the samples and pulled normal to the substrate by known weights; the epoxy failure limit was typically ~70 MPa, and this thus determined the instrumental limit.

2.4 Procedure

Substrate samples were cleaned with alcohol and positioned within the vacuum chamber for the plasma deposition and ion bombardment processing. The oil-free system was cryogenically pumped down to a base pressure of about 1×10^{-6} Torr or better before commencing the plasma process. Oxygen gas was admitted to a pressure of typically 10 to 15 mTorr, and the plasma deposition and ion bombardment processing carried out as described above; the time required for film growth was usually a few tens of minutes. Note that in this plasma processing the energy added to the sample is small and they are not heated significantly. The samples were then removed from the chamber for characterization and testing. Heating was done in air in an oven which could be heated to 1100°C. The samples could be inserted into and removed from the hot oven quickly, and the sample heat-up and cool-down time was thus just a few minutes, determined by the thermal capacity of the small coupons. In the experiments conducted, the samples were maintained at full temperature at times varying between 15 minutes and 16 hours.

3. EXPERIMENTAL RESULTS

Alumina samples were prepared and studied, both on silicon carbide and iron aluminide substrates. Several different thicknesses of films were formed, between about 0.2 μ and 1.5 μ . Issues that we considered important to address were:

- Stoichiometry of the plasma deposited film, both pre- and post-heat treatment;
- Crystallographic phase of the film produced, pre- and post-heat treatment;
- Adhesion of the film to the substrate, pre- and post-heat treatment;
- Adhesion of the film to the substrate following thermal cycling of the sample through a number of repeated high temperature excursions.

3.1 Stoichiometry

RBS analysis showed that the as-prepared samples were usually slightly oxygen-rich, with composition such as for example $\text{Al}_2\text{O}_{3.3}$ for an oxygen pressure of 12 mTorr. When the oxygen pressure was too high, for example 26 mTorr as in our early work, the films were significantly oxygen rich, with an Al_2O_5 composition. The post-heating films were, not surprisingly, of good Al_2O_3 stoichiometry.

3.2 Crystallography

The as-deposited alumina was typically amorphous with a small amount of $\kappa\text{-Al}_2\text{O}_3$, but for optimized plasma and ion beam processing conditions and oxygen gas pressure, we could form material containing largely α - and $\kappa\text{-Al}_2\text{O}_3$ (Fig. 3). The post-heating films were always largely $\alpha\text{-Al}_2\text{O}_3$ (Fig. 4).

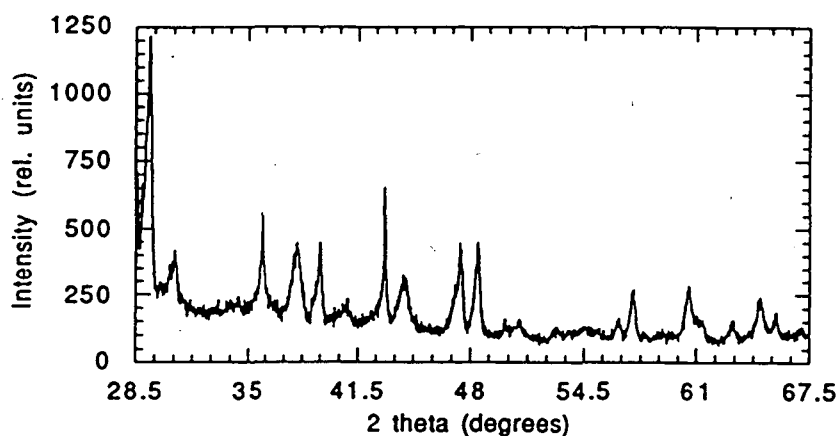


Figure 3. X-ray diffraction spectrum for an alumina film, as-deposited (pre-heating) at optimal conditions, indicating mostly α - and $\kappa\text{-Al}_2\text{O}_3$ phases. Film thickness $0.5\ \mu$; on FeAl.

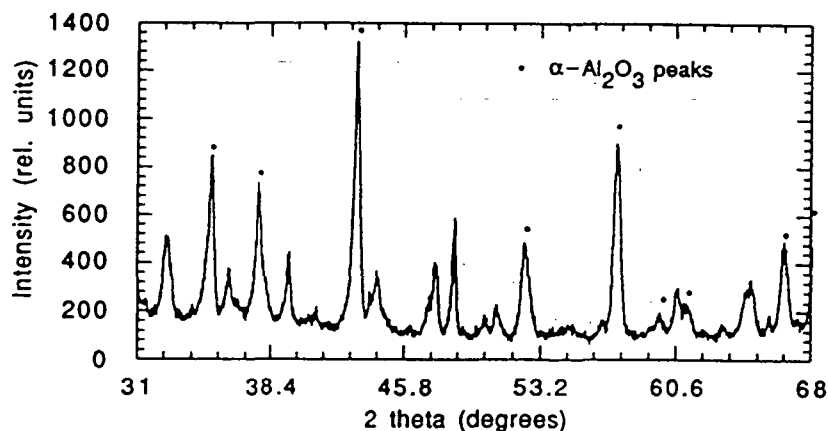


Figure 4. X-ray diffraction spectrum for an alumina film, after heating at 1000°C for 16 hours, indicating mostly $\alpha\text{-Al}_2\text{O}_3$ phase. Film thickness $0.5\ \mu$; on FeAl.

3.3 Adhesion

The film-substrate adhesion was always good for the as-prepared, pre-heat-treatment films – an adhesion strength as measured with our home-made Sebastian-type pull tester of ≥ 70 MPa, the instrumental limit of measurement – this for both alumina and chromia films on both iron aluminide and silicon carbide. Post-heat-treatment, the adhesion strength of the optimally-prepared films is also good for films of thickness $\leq 0.5 \mu$, but we have had mixed results to-date with films of thickness $\geq 1 \mu$. We refer here to heating to 1000°C for a period of either 15 minutes or 16 hours (we have done both), for a single heat cycling.

3.4 Adhesion after Repeated Thermal Cycling

We have obtained data for an alumina film of thickness about 0.25μ formed on a SiC substrate. The sample was thermally cycled from room temperature to 1000°C though four cycles of 15 minutes duration each; heating and cooling time of the sample was one or two minutes only. The film-substrate adhesion both before and after temperature cycling was excellent, at the instrumental limit of the pull-tester.

4. CONCLUSION

Films of alumina and chromia have been plasma synthesized on FeAl and SiC substrates. The process is straightforward and produces a mostly $\alpha\text{-Al}_2\text{O}_3$ phase. The plasma deposition process is accompanied by a controlled and time-varied ion bombardment such that the film is atomically mixed to the substrate and consequently of high adhesion, and the ion-assist process during the bulk of the film growth helps to form good morphology. For optimally prepared films the film-substrate adhesion is ≥ 70 MPa, and at least for quarter-micron alumina films on SiC the film retains its integrity and full adhesion strength through a 4-cycle thermal cycling between ambient and 1000°C .

We have reported here on the work we have done in a preliminary exploratory program on the feasibility of the plasma synthesis of alumina and chromia films on silicon carbide and iron aluminide substrates. There is much work that remains to be done. We can conclude, however, that the plasma and ion beam techniques that we have developed provide a tool that could be valuable for the formation of highly adherent and thermally tolerant ceramic films.

References

1. I.G. Brown, A. Anders, S. Anders, M.R. Dickinson, I.C. Ivanov, M.A. MacGill, X. Yao and K.M. Yu, Nucl. Instrum. Meth. Phys. Res. B80/81, 1281 (1993).
2. Ian Brown, in *Plasma Synthesis and Processing of Materials*, edited by K. Upadhyaya (pub. TMS, Warrendale, PA, 1993).
3. A. Anders, S. Anders, I.G. Brown and I.C. Ivanov, Mat. Res. Soc. Symp. Proc. 316, 833 (1994).
4. A. Anders, S. Anders, I.G. Brown, M.R. Dickinson and R.A. MacGill, J. Vac. Sci. Tech. B12, 815 (1994).
5. See, for instance, *Vacuum Arcs - Theory and Application*, edited by J.M. Lafferty, (Wiley, N.Y., 1980).
6. See, for instance, *Vacuum Arc Science and Technology*, edited by R.L. Boxman, P. Martin and D. Sanders, (Noyes, N.Y., 1995).
7. S. Anders, A. Anders and I.G. Brown, J. Appl. Phys. 74, 4239 (1993).
8. A. Anders, S. Anders and I.G. Brown, Plasma Sources Sci. Technol. 4, 1 (1995).
9. S. Anders, A. Anders and I.G. Brown, J. Appl. Phys. 75, 4895 (1994).
10. R.A. MacGill, S. Anders, A. Anders, R.A. Castro, M.R. Dickinson, K.M. Yu and I.G. Brown, "Cathodic Arc Deposition of Copper Oxide Thin Films", submitted to Surface and Coatings Technol.
11. S. Anders, A. Anders, M. Rubin, Z. Wang, S. Raoux, F. Kong and I.G. Brown, "Formation of Metal Oxides by Cathodic Arc Deposition", paper presented at the Int. Conf. on Metallurgical Coatings and Thin Films, San Diego, CA, Apr 24-28, 1995.
12. I.G. Brown, Rev. Sci. Instrum. 10, 3061 (1994).

DISTRIBUTION

AIR PRODUCTS AND CHEMICALS

P.O. Box 538
Allentown, PA 18105
S. W. Dean

ALBERTA RESEARCH COUNCIL

Oil Sands Research Department
P.O. Box 8330, Postal Station F
Edmonton, Alberta
Canada T6H5X2
L. G. S. Gray

ALLISON GAS TURBINE DIVISION

P.O. Box 420
Indianapolis, IN 46206-0420
P. Khandelwal (Speed Code W-5)
R. A. Wenglarz (Speed Code W-16)

AMAX R&D CENTER

5950 McIntyre Street
Golden, CO 80403
T. B. Cox

ARGONNE NATIONAL LABORATORY

9700 S. Cass Avenue
Argonne, IL 60439
W. A. Ellingson
K. Natesan

ARGONNE NATIONAL LABORATORY-WEST

P.O. Box 2528
Idaho Falls, ID 83403-2528
S. P. Henslee

AVCO RESEARCH LABORATORY

2385 Revere Beach Parkway
Everett, MA 02149
R. J. Pollina

BABCOCK & WILCOX

1562 Beeson St.
Alliance, OH 44601
T. I. Johnson

BABCOCK & WILCOX

Domestic Fossil Operations
20 South Van Buren Avenue
Barberton, OH 44023
M. Gold

BETHLEHEM STEEL CORPORATION

Homer Research Laboratory
Bethlehem, PA 18016
B. L. Bramfitt
J. M. Chilton

BRITISH COAL CORPORATION

Coal Technology Development Division
Stoke Orchard, Cheltenham
Glostershire, England GL52 4ZG
J. Oakey

CANADA CENTER FOR MINERAL & ENERGY TECHNOLOGY

568 Booth Street
Ottawa, Ontario
Canada K1A 0G1
R. Winston Revie
Mahi Sahoo

COLORADO SCHOOL OF MINES

Department of Metallurgical Engineering
Golden, CO 80401
G. R. Edwards

DOE

DOE OAK RIDGE OPERATIONS

P. O. Box 2008
Building 4500N, MS 6269
Oak Ridge, TN 37831
E. E. Hoffman

DOE

DOE OAK RIDGE OPERATIONS

P. O. Box 2001
Oak Ridge, TN 37831
Assistant Manager for
Energy Research and Development

DOE
IDAHO OPERATIONS OFFICE
P. O. Box 1625
Idaho Falls, ID 83415
R. B. Loop

DOE
MORGANTOWN ENERGY TECHNOLOGY
CENTER
P.O. Box 880
Morgantown, WV 26505
R. C. Bedick
D. C. Cicero
F. W. Crouse, Jr.
N. T. Holcombe
W. J. Huber
J. E. Notestein

DOE
OFFICE OF FOSSIL ENERGY
FE-72
19901 Germantown Road
Germantown, MD 20874-1290
J. P. Carr

DOE
OFFICE OF BASIC ENERGY SCIENCES
Materials Sciences Division
ER-131 GTN
Washington, DC 20545
J. B. Darby

DOE
OFFICE OF SCIENTIFIC AND TECHNICAL
INFORMATION
P. O. Box 62
Oak Ridge, TN 37831
For distribution by microfiche as shown in
DOE/TIC-4500, Distribution Category:
UC-114 (Coal Based Materials and
Components)

DOE
PITTSBURGH ENERGY TECHNOLOGY
CENTER
P.O. Box 10940
Pittsburgh, PA 15236
A. L. Baldwin
G. V. McGurl
R. Santore
T. M. Torkos

EC TECHNOLOGIES INC.
3614 Highpoint Drive
San Antonio, TX 78217
D. J. Kenton

ELECTRIC POWER RESEARCH
INSTITUTE
P.O. Box 10412
3412 Hillview Avenue
Palo Alto, CA 94303
W. T. Bakker
J. Stringer
R. Wolk

EUROPEAN COMMUNITIES JOINT
RESEARCH CENTRE
Petten Establishment
P.O. Box 2
1755 ZG Petten
The Netherlands
M. Van de Voorde

FOSTER WHEELER DEVELOPMENT
CORPORATION
Materials Technology Department
John Blizard Research Center
12 Peach Tree Hill Road
Livingston, NJ 07039
J. L. Blough

IDAHO NATIONAL ENGINEERING
LABORATORY
P.O. Box 1625
Idaho Falls, ID 83415
A. B. Denison
R. N. Wright

LAWRENCE BERKELEY LABORATORY
University of California
Berkeley, CA 94720
Ian Brown

LAWRENCE LIVERMORE NATIONAL
LABORATORY
P.O. Box 808, L-325
Livermore, CA 94550
W. A. Steele

NATIONAL MATERIALS ADVISORY
BOARD
National Research Council
2101 Constitution Avenue
Washington, DC 20418
K. M. Zwilsky

OAK RIDGE NATIONAL LABORATORY
P.O. Box 2008
Oak Ridge, TN 37831
P. T. Carlson
N. C. Cole
R. R. Judkins
C. T. Liu
R. A. Lawson (8 copies)
C. G. McKamey
V. K. Sikka
R. W. Swindeman
P. F. Tortorelli
I. G. Wright

PACIFIC NORTHWEST LABORATORY
P. O. Box 999, K3-59
Battelle Boulevard
Richland, WA 99352
R. N. Johnson

SHELL DEVELOPMENT COMPANY
P. O. Box 1380
Houston, TX 77251-1380
L. W. R. Dicks

THE JOHNS HOPKINS UNIVERSITY
Materials Science & Engineering
Maryland Hall
Baltimore, MD 21218
R. E. Green, Jr.

THE MATERIALS PROPERTIES COUNCIL,
INC.
United Engineering Center
345 E. Forty-Seventh Street
New York, NY 10017
M. Prager

THE TORRINGTON COMPANY
Advanced Technology Center
59 Field Street
Torrington, CT 06790
W. J. Chmura

UNION CARBIDE CORPORATION
Linde Division
P.O. Box 44
175 East Park Drive
Tonawanda, NY 14151-0044
Harry Cheung

UNIVERSITY OF WASHINGTON
Department of Materials Science
and Engineering
101 Wilson, FB-10
Seattle, WA 98195
T. G. Stoebe

UNIVERSITY OF TENNESSEE SPACE
INSTITUTE
Tullahoma, TN 37388
J. W. Muehlhauser

UNIVERSITY OF TENNESSEE AT
KNOXVILLE
Materials Science and Engineering
Department
Knoxville, TN 37996
P. Liaw
C. D. Lundin

WESTERN RESEARCH INSTITUTE

365 N. 9th Street
P.O. Box 3395
University Station
Laramie, WY 82071
V. K. Sethi

**WESTINGHOUSE ELECTRIC
CORPORATION**

Research and Development Center
1310 Beulah Road
Pittsburgh, PA 15235
S. C. Singhal

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720