MAY 28, 1996

**WEAR RESISTANT COMPOSITE STRUCTURE OF VITREOUS CARBON
CONTAINING CONVOLUTED FIBERS**

FINAL REPORT FOR:

GRANT NUMBER DE-FG01-94CE15613

U. S. DEPARTMENT OF ENERGY, ENERGY RELATED INVENTIONS PROGRAM
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ABSTRACT:

Energy Related Inventions Program Number 613 was a two year program to commercialize a unique new wear material, Metal Reinforced Carbon Composite, MRCC. The program was designed to manufacture sample components of MRCC for evaluation by potential users and manufacturers. As a result of the program Burton Technologies Inc. and Rotary Power International are forming a joint company to manufacture, market and license MRCC materials to a wide range of industries.

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EXECUTIVE SUMMARY:

A two year program was undertaken to commercialize Metal Reinforced Carbon Composite materials in the US market. This family of materials has unique properties of low friction and wear, chemical resistance, and high temperature durability. The program was designed to manufacture sample components for evaluation by potential users and manufacturers. Laboratory specimens were also to be provided to outside laboratories for independent testing. Contacts were made with 25 manufacturing or using companies and organizations. Laboratory tests were performed by 7 outside independent laboratories and a paper was published at the 1995 Society of Tribologist and Lubrication Engineers Annual meeting using data taken at 4 US government laboratories. In addition to the assistance provided by the Department of Energy through this grant, assistance was also received from 7 organizations, private, state, and federal.

The final status of the program is that Burton Technologies is entering into partnership with Rotary Power International to form a joint company to manufacture, distribute and license MRCC products and technology. Serious evaluation of MRCC is underway at several of the companies contacted during this program. These companies are to be the first customers of the new joint company.

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BACKGROUND

Metal Reinforced Carbon Composite, MRCC, is a patented proprietary material developed by Burton Technologies Inc.. MRCC has a unique set of properties consisting of extremely low friction, very long wear, high chemical resistance, stability at high temperature, and the ability to maintain these properties in inert or vacuum atmospheres. Because the material is metal-fiber reinforced the thermal and electrical conductivity can be varied not only in magnitude but in direction as well by aligning the fibers along a selected axis. Data on MRCC were submitted to the National Institute of Standards and Technology for evaluation and a recommendation was made to the Department of Energy to fund the commercialization of this material, this became Energy Related Inventions Program project Number 613.

Prior to the DoE funding Burton Technologies had performed a broad material development program to explore the range of MRCC which grew from one formula to a whole family of materials with varying properties which could be tailored to particular applications. A complete list of these properties is included as Appendix D. As an example however the reinforcing material in the composite consists of continuous metal fibers of many meters in length. The weight content on these fibers in the composite material can range from 0.0% to over 90.0%. Therefore a wide range of material properties is available.

In initial approaches to companies to introduce the MRCC materials, we had little success, because we only had the capacity to manufacture small laboratory-sized specimens. Companies were unwilling to test these samples without the assurance that they would be able to evaluate full-sized prototype components. The ERIP program was designed to cross that barrier by allowing us to manufacture full-sized machine components.

There was some concern that the delays in obtaining government funding would cause the market opportunity to be missed. This was not the situation for two principal reasons;

1. No competing technology has been developed.
2. The state of the US manufacturing economy in the early 1990's was one of retreat rather than one of expansion, coming as it did near the end of a multi-year recession. The beginning of ERIP project 613 came just as the economy began to expand. Companies were still cautious and reluctant

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even to try new technology but they were willing to listen.

ERIP 613 targeted selected manufacturing companies where the pressures of the world markets were pushing the existing materials beyond their safe limits.

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DESCRIPTION OF THE PROGRAM

Program Goals: This program was designed to introduce Metal Reinforced Carbon Composite, MRCC, materials to potential manufacturers of components and devices. The strategy for this introduction was to provide drop-in components manufactured from MRCC to be installed in their products for direct comparison with their existing parts. The industries that we had targeted as a result of prior experience are listed in Table 1 below.

TABLE 1

1. Manufacturers of Brake and Clutch Friction Materials
2. Manufacturers of Seals for Long-life/Hostile Environment
3. Manufacturers of Bearings for High Stress Applications
4. Manufacturers of Compressors
5. Manufacturers of Current Collectors for Railroads
6. Test Specimens for Outside Laboratories to Evaluate

Description of Typical Company Contacts: At the beginning of the ERIP program we were in contact with industrial companies in all of the fields listed in Table 1. All of these companies had expressed interest in improving their products, and in all cases indicated that they were considering advanced designs which were material limited. The early months on the ERIP program were devoted to reestablishing contact with all of these companies and extending the list of contacts to identify as many serious potential users of MRCC as we could. As a result of these early contacts we were able to establish a standard size mold to manufacture MRCC blanks from which all of the differing components could be constructed, and which was compatible with our existing furnace and other fabrication equipment. We also renewed old ties and established some new contacts in Independent Laboratories, especially US Government Laboratories. The Government Laboratories are well respected world wide for the objectivity of their technical work. Even though we had amassed a great deal of technical information and test results on MRCC materials, the reassurance from favorable tests by independent laboratories was needed. Table 2 below lists the companies and laboratories contacted. In the cases of the industrial firms many of these contacts have still not come to any conclusion. This is not because of any failing of MRCC materials but a reflection of the cautious state of the companies themselves. Many of the

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companies in Table 2 have been subject to a takeover or a reorganization during the course of this program. In some cases the divisions with which we were in contact were eliminated or were subjected to a mission change.

We experienced four broad types of contacts with our target companies which are described below. Some of these were positive, some neutral and some negative.

Frick Compressors was the most vivid example. We were invited warmly to a plant face-to-face visit in Pennsylvania. Less than 24 hours later when we arrived for the scheduled visit we were met with actual hostility, and a flat rejection of any sort of future discussions. Not being willing to drive across three states and return empty handed we did receive a verbal agreement for Frick to perform some simple but useful hostile fluid stability tests. We supplied coupon pieces of a grade of MRCC which we felt would be correct for their fluids. To our knowledge these tests were never performed.

Westinghouse has been an example of another kind of dry-contact. In their case they have been reorganized more than once during our discussions, and although the quality of the contacts has been good, with clear communication and mutual understanding of the technical issues involved, even after at least two face-to-face meetings they have been unable to respond due to organizational concerns. These contacts are still alive and we have confidence that when the corporation stabilizes we will find a place there.

A third type of contact is exemplified by PolyCorr/Advanced Polymer Technologies. This is a somewhat loose organization, as are many small manufacturing concerns. Although they were highly interested in MRCC technology and licensing discussions reached an advanced stage these eventually fell through because they did not really have the means to carry out their ambitions.

There were also contacts where, after the exchange of technical information, we found that there was no real application for the MRCC materials.

Then there was the best type of contact, a company with a need and the vision to look beyond stop-gap fixes to real advances in their products. In the course of this program we also encountered these companies. They are Rotary Power International, W. R. Brown Company, Railroad Friction

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Products, United Technologies, and TransTech.

Rotary Power International has purchased an option for the rights to MRCC products and we are going into a joint venture to manufacture, license and distribute MRCC products.

We have advanced beyond initial tests to advanced testing in the case of the other companies.

Table 2 lists the companies contacted during the program.

TABLE 2

1. TransTech of SC
2. Frick Compressors
3. Carbonne Lorraine of North America
4. John Crane
5. Timkin
6. Exxon
7. Carrier Corporation
8. Westinghouse
9. Rotary Power International
10. Rotorex
11. ThermoKing
12. Kaydon Corporation
13. Sullair
14. Polymer Products Incorporated
15. Advanced Polymer Technologies/PolyCorr
16. Agie
17. Carbon-Carbon Advanced Technologies
18. United Technologies
19. Schunk Graphite
20. Railroad Friction Products
21. Hitachi Seiki U.S.A., Inc.
22. DaeWoo
- Other Organizations:
23. NASA Goddard
24. NASA Greenbelt
25. NASA Langley

Laboratory Contacts: We also contacted outside laboratories. The results of these contacts were very concrete. Through the Institute for Gas Technology and Dr. Jerry Wurm we established a relationship with W. R. Brown Compressor company, advanced our discussions with Westinghouse and a couple of its Divisions, and advanced our relationship with Rotary Power International to partnership.

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With the results of experiments by Dr. Michael Dugger at Sandia National Laboratory, Dr. Ali Erdmer at Argonne National Laboratory, Dr. Peter Blau at Oak Ridge National Laboratory, and Dr. Harold Sliny at NASA Lewis Research Center we published a paper through the Society of Tribologists and Lubrication Engineers. This paper was presented in Chicago at the 50TH STLE Annual meeting in May of 1995. This has been a useful handout for technical properties taken independently.

Additionally we are participating in a study at the North Carolina State University School of Veterinary Medicine evaluating MRCC and other advanced materials for use as prosthetic replacement bone joints. This program is ongoing at the time of this report and the major thrust awaits funding. The initial stage of Invitro testing for tissue compatibility is underway. The biological information obtained from these experiments will be useful in future human applications.

Carbone Lorraine of North America has tested of MRCC for conductivity and other material properties, and is presently running brush tests.

The testing by outside laboratories has been useful in providing independent technical information and in obtaining corporate contacts for business relationships.

Table 3 lists the outside laboratories involved with this program.

TABLE 3

1. Sandia National Laboratory
2. Argonne National Laboratory
3. Oak Ridge National Laboratory
4. NASA Lewis Research Center
5. The Institute for Gas Technology at IIT
6. North Carolina State University School of Veterinary Medicine
7. Carbone Lorraine of North America

As the program ends both Dr. Dugger and Dr. Erdmir have requested further specimens for some advanced studies.

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Other Sources of Support: We have also utilized the assets that the ERIP program has made available to us. We have made great use of a flyer prepared by James Ball for National Institute for Standards and Technology which contains the magic words "endorsed by NIST". A copy of this flyer is in appendix A. Additionally we received an invitation to participate in the Innovative Concepts Program also sponsored by DoE at their show in Denver in March 1995. Turnout for the show was hampered by terrible weather, but we did get a second excellent flyer prepared by Battelle Pacific Northwest Laboratory. This flyer contained less technical information than the NIST flyer but was easier for nontechnical people to understand. This has also been a useful handout. A copy of this flyer is also in appendix A. A third flyer and a new Logo has been prepared for us by Rotary Power International and a copy of this is also attached in Appendix A.

The Center for Innovation and Business Development at the University of North Dakota prepared a market survey for us exploring the fields of refrigeration and heat exchangers for corrosive fluids. this is of interest to the chemical, energy, and geothermal energy industries. (We have contacted this center recently to commission another study for mechanical carbon applications). This was a professional study and Jon Freeland has received permission from us to use the survey as a training example in his program.

We have also received assistance from our local Small Business Technology and Development Center, the Industrial Extension service of North Carolina State University, and The Triangle University Consortium. They have all provided some resources and information, mainly in the contacting of manufacturing companies with potential interest in MRCC.

We have also been in contact with the Japanese External Trade Organization, (JETRO), which is a Japanese government organization charged with introducing American Manufacturers to Japanese Industrial Companies. This has resulted in six requests for information most notably from Hitachi Seiki. We were one of the few North Carolina Companies presented at the 1996 Annual JETRO show in New York this spring. Table 4 lists the outside organizations which provided assistance to this ERIP program.

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TABLE 4

1. DoE/NIST Manufacturing Extension Partnership.
2. Batelle Pacific Northwest Laboratory/ Innovative Concepts Program
3. NC Small Bussiness Technology and Development Center
4. Triangle University Licensing Consortium
5. North Carolina State University Industrial Extension Service
6. Center for Innovation and Business Development, University of North Dakota
7. Japanese External Trade Organization

Status at end of ERIP Program:

Burton Technologies Inc. and Rotary Power International are jointly forming of a new corporation to manufacture, distribute, and license MRCC products and technology.

Advanced testing is in progress with the W. R. Brown Company.

United Technologies has included us in their new product program and have sent a purchase order for preproduction test components.

Following initial large-scale tests advanced specimens are being supplied to Railroad Friction Products.

An advanced bushing design is being supplied to NASA.

A pantograph component is being supplied to TransTech.

These companies are expected to be the first production customers of the new joint company.

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SUMMARY:

An ambitious program was undertaken to identify industrial companies which had advanced products on-the-board and were experiencing material problems in the areas of wear life, chemical resistance, high temperature applications, hostile or vacuum applications, or high electrical current capacity. Typically these would be applications where polymer materials had been pushed beyond their envelope of operation. Once these opportunities were identified then drop-in components would be made for side-by-side evaluation with the existing components. Companies were identified, tests were run, results were evaluated with the result being a joint venture between Burton Technologies Inc. and Rotary Power International to supply these markets.

During the program assistance was received from national laboratories, industrial firms, government agencies, and others. In spite of this and all of the assistance provided by the ERIP program this was not a simple process. The business climate in the USA today is not one of innovation but rather one of increasing efficiency. In general product lines are not being advanced in design. Instead ways are being sought to reduce costs of the existing products made with existing machinery. Eventually we found forward looking partners who are interested in advancing their present field while expanding into new markets. We are looking forward to expanding the applications for MRCC materials. The first products to reach consumers will open the doors to many new applications. It will be interesting to see how wide the eventual applications will be.

Based on our evaluation of existing companies involved in materials manufacture the joint company should create about 100 new US manufacturing jobs.

APPENDIX A

Adaptable Metal Reinforced Carbon Composites

Ralph A. & Gaines Burton
Burton Technologies
Patent No. 5,182,186
ERIP 613

This process produces a tailored composite material that can be used without any lubricants, is compatible with high-temperature and hostile chemical environments, and can be applied to large components and structures.

NIST

Sponsored by
The Energy Related Inventions Program
of
The Department of Energy
and
The National Institute of Standards
and Technology

Introduction

Metal Reinforced Carbon Composites (MRCC) are a new class of material made up of non-graphitic, continuous phase,

unstructured carbon binder and continuous metal fibers. These composites are self lubricating,, chemically resistant, impervious, light weight, have controllable conductivity, and are adaptable for applications up to 400°C in vacuum, ambient, or hostile chemical environments.

Process Description

This process is a simple single stage pyrolysis of a resin formed greenbody. Machining can be performed on the greenbody or on the final fired component, depending on required tolerances.

Material Properties

Self Lubricating - when run dry, has lower friction and wear than conventional materials when run lubricated. Use avoids wear contamination of lubricant streams and eliminates potential for catastrophic failure in high

speed rotary components.

Impermeable - material is impervious to diffusion when used in seal systems, thus making it exceptionally useful in air conditioning and other high pressure chemical containment system components.

Chemically Resistant - the binding matrix of MRCC is a continuous glassy phase of unstructured carbon which is completely invulnerable against chemical attack from most acids, bases, and other corrosives.

Light Weight - MRCC can be made in grades which have 50% the specific gravity of conventional carbon graphite copper materials.

Light weight composites are especially efficient in dynamic components such

as pistons and other moving parts. The MRCC process applies not only to small parts, but also to large castings such as pump bodies and compressor cylinders.

Controlled Strength and Conductivity - use of continuous metal fibers allow thermal and electrical conductivity material properties to be widely varied, thus opening up a host of applications.

High Temperature Tolerance - Dynamic tests have verified the integrity of MRCC materials for wear up to 425°F. Static tests subjected specimens to temperatures of 3000°F without loss of integrity.

Vacuum and Dry Atmosphere - the ability to run in dynamic tribological applications without lubrication makes MRCC components ideal for aerospace and chemical applications.

Economic and Market Potential

This process produces a composite material consisting of a vitreous carbon matrix containing convoluted fibers. The product has an extremely high wear resistance, is tolerant to almost all hostile fluids and atmospheres, can be fabricated in large sizes, without difficulty, and has a higher electrical conductivity than competing materials. Any

of the material characteristics can be optimized for specific applications by the choice of fiber in the matrix and by adjusting the process parameters.

Applications

Applications for these tailored materials include:

- Current Collectors, including motor brushes, sliprings, railroad pantographs and other high temperature electro-magnetic applications
- Tip seals for rotary Engines, compressors.
- Seals, vanes, bushings, bearings, and gears.
- Heat Exchangers
- Prosthetics

Current Status

Development of a family of materials has been completed. Specimens of up to 2" diameter and 8" in length can be produced with current equipment. Larger components will require a scaling up of the current equipment. Product development in the form of formula selection for specific applications is now underway.

Future Directions

Burton Technologies can provide drop-in prototype specimens for evaluation by equipment manufacturers with the goal of direct licensing of the process and material. Burton

Technologies does not intend to manufacture specific materials or components, however can arrange for the manufacture of component parts with other manufacturers.

Material samples have been tested by three independent laboratories and data are available for specific applications.

A detailed market analysis of applications is also available for review by potential investors.

This technology has been evaluated and endorsed by the National Institute of Standards and Technology (NIST) and its development sponsored in part by the Department of Energy as part of the Energy-Related Inventions Program. This information is provided through the NIST Manufacturing Extension Partnership network to promote American economic growth and competitiveness through the deployment of Federally-sponsored technology.

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Adaptable, Metal-Reinforced Carbon Composites

Ralph A. Burton and
Gaines Burton
Burton Technologies

An innovative process produces a tailored, composite carbon material that can be used to manufacture wear and structural components that do not require any lubricants. The process is compatible with high temperatures up to 400°C and with hostile environments.

Cross Section of MRCC Grade 300 (~300X)

Introduction

Moving parts fabricated from commercially available material generally require a lubricant. The use of lubricants can create several problems: explosions in the compressed gas industry; contamination of the fluids being pumped in the refrigeration, food processing, and chemical

industries; and a tendency to boil off in aerospace applications. Using lubricants adds energy, maintenance, and supply costs, and creates environmental concerns.

Concept Description

Metal-reinforced carbon composites (MRCC) that require no lubricant are a new class of material made up of nongraphitic, continuous-phase, unstructured carbon binder and continuous metal fibers. A noteworthy advantage of the MRCC process is that it can be applied not only to small parts, such as bearings and seals, but also to large castings, such as pump bodies and compressor cylinders.

The process for manufacturing the MRCC is a simple, single-stage pyrolysis of a resin-formed greenbody, i.e., metal and carbon composite particles held together by binder or resin. Machining can be performed on the greenbody or on the final fired component, depending on required tolerances.

The MRCC material offers several desirable features:

- Self-lubricating - When run in a dry condition, the material has lower friction and wear than conventional materials that are run lubricated. The chances of contamination of lubricant streams and the potential for catastrophic failure in high-speed rotary components, such as jet engines and large computer coolant systems, are almost eliminated.

- **Impermeable** - The material is impervious to diffusion when used in seal systems, which makes it exceptionally useful in air-conditioning and other high-pressure, chemical-containment-system components.
- **Chemically resistant** - The binding matrix of MRCC is a continuous glassy phase of unstructured carbon, which is completely invulnerable to chemical attack from most acids, bases, and other corrosives.
- **Lightweight** - MRCC can be made in grades that have 50% of the specific gravity of conventional, graphite/copper materials. These lightweight composites are especially efficient in dynamic components, such as pistons and other moving parts.
- **Controlled strength and conductivity** - The continuous metal fibers allow for control of the properties of the thermal and electrical conductivity material. Selective cooling of high-temperature components opens up many possible applications of the process.
- **High-temperature tolerance** - The integrity of MRCC materials has been verified for wear up to 218°C. No loss of integrity occurred when specimens were subjected to temperatures of 1,650°C in static tests.
- **Vacuum and dry atmosphere** - MRCC components do not require special atmospheres for high performance; the components' wear performance in a vacuum atmosphere is actually superior to that in air.

Economics and Market Potential

MRCC costs can be well under \$1.75/lb, depending on the metal content. Its cheapest competitor, electrode carbon, which is essentially a pencil lead material, costs over \$2/lb. The nearest performance competitor, chemical vapor deposition (a coating process for conventional materials), is very expensive. It costs about \$1,000 to have a component coated with a thickness of a few thousandths of an inch--of almost an intangible weight. Another competitor, low-temperature diamond material, is too new to evaluate economically, but it is expected to cost many thousands of dollars per pound--if it is even feasible and/or practical to produce in large quantities.

Any of the material characteristics of MRCC can be optimized for specific applications by choosing the appropriate fiber in the matrix and by adjusting the process parameters. A detailed market analysis of applications is available for review by potential investors. These applications include

- current collectors (motor brushes, slip rings, railroad pantographs, and other high-temperature and electromagnetic applications)
- mechanical components (tip seals for rotary engines compressors, seals, vanes, bushings, bearings, gears, and piston rings for engines)
- biomedical needs (prosthetics and valves).

Key Experimental Results

Material samples have been tested by four independent laboratories: NASA and three U.S. Department of Energy laboratories. Information on these tests is available upon request.

A family of MRCC materials has been developed by Burton Technologies. Specimens of up to 2-in. diameter and 8-in. long can be produced now, and larger components will be possible when the equipment is scaled up. Formula selection for custom applications is under development.

Future Development Needs

Burton Technologies can provide drop-in prototype specimens for evaluation by equipment manufacturers who may directly license the process and material. Burton Technologies does not plan to manufacture specific materials or components, but can make arrangements with other manufacturers.

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APPENDIX B

DRAFT

WEAR-RESISTANT COMPOSITE STRUCTURE OF VITREOUS CARBON CONTAINING CONVOLUTED FIBERS

ERIP Recommendation 613

Prepared for

**U.S. Department of Energy
Office of Inventions and Innovation**

by

NCAT Development Corporation

**Investigator: Jonathan G. Freeland, Manufacturing Consultant
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Submitted: May 9, 1994

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PROJECT REVIEW

EXECUTIVE SUMMARY

Overview

Carbon-based composite materials have been utilized in a variety of applications, especially in the 1990s. Despite higher costs, composite materials have been extremely successful because of outstanding performance characteristics.

In the mid-1980s, growth for composite materials had reached 25 percent per year; however, demand has slowed to an annual growth rate of 6.2 percent due to substantial reductions in defense and commercial aviation industry. This decrease in demand would have been significantly greater, but composite prices have dropped allowing these materials to become more competitive in markets that were previously limited because of cost restrictions.

The subject invention, "Wear-Resistant Composite Structure of Vitreous Carbon Containing Convulated Fibers," is an innovative new material that substantially improves performance characteristics over existing composite materials. This innovation has the ability to operate in high-temperature and hostile environments, while still maintaining its desirable characteristics.

Identified Market Potential

If industry experts' predictions are correct, a new record will be set in 1994 for total industry shipments of composite materials. North American shipments are expected to rise from 2.6 billion pounds in 1993 to 2.8 billion pounds in 1994. Steady production of durable goods, controlled inflation, low interest rates, stable oil prices, and expanded housing development are contributing factors in the increase.

Industries subject to high corrosion rates will drive the demand for composite reinforcements upward by 1.1 percent. An estimated 337 million-pound market in 1993, this increase is attributed to improvements in infrastructure resulting from substitution of glass-reinforced pipes for metal pipes.

Significant market potential exists in several market niches. At the request of the inventors, the compressor and heat exchanger markets were analyzed because of the significant potential and their relatively little knowledge of the market.

Compressors

- ▶ In 1992, manufacturers' shipments of pumps and compressors totaled \$5.157 billion (16.4 million units), an increase of 1 percent from 1991 figures. These pumps and compressors are used in almost every major U.S. industry, ranging from heavy industrial applications to automobiles.
- ▶ Corporations, such as Sullair Refrigeration, have had substantial difficulties keeping bearings and seals lubricated by oil where ammonia is the refrigerant (ammonia acts as a cleaning agent). Industry experts expressed a keen interest in the subject invention as they are currently looking for an alternative.

Heat Exchangers

- ▶ The total U.S. market in 1991, comprising all end-use sectors and all types of heat exchangers, amounted to \$1.66 billion and is forecasted to reach \$1.9 billion by 1995. Additionally, the European heat exchanger market offers significant potential, growing to \$3.46 billion in 1994.
- ▶ A significant market niche for the subject invention was found where heat exchangers operate in high-temperature and hostile environments, primarily in the chemical production industry. Presently, 15 companies are competing for \$30 million in sales (approximately 300 units), in this high-profit and extremely competitive market niche.

Competitive Environment

Research and development efforts in the area of composites are arduous and expensive tasks. Researchers, especially in smaller technology-driven firms, often develop materials without identified market demand. Applications are pursued after the fact and are often very difficult to match with desired performance characteristics.

Several applications that are in high-temperature and hostile environments, including both compressors and heat exchangers, are utilizing advanced materials. These materials are expensive relative to their performance characteristics.

Barriers/Keys to Market Entry

Because of the number of advanced materials currently available, potential users are often inundated with options and, consequently, attempts to commercialize the subject invention may be hindered. The development of a specification sheet detailing competitive advantages, performance properties, and product cost estimates will be crucial in order to educate potential customers.

Qualified testing in specific environments will be necessary, although expensive, in order to prove the subject invention's suitability in new applications. Collaboration with private industry may be necessary to conduct this testing and also to manufacture the final product. Further research into these and other market niches will be necessary to successfully commercialize the subject invention.

I. Introduction

The subject of this evaluation is a wear-resistant composite structure of vitreous carbon containing convoluted fibers. The immediate market identified is in most mechanical devices with lubricated seals and bearings and devices that operate in high-temperature and hostile environments. Initially, composite materials were very expensive; therefore, only high-priced, high-technology applications, such as defense and commercial aviation industries, were able to utilize these products. Process improvements and product innovations have allowed the price of composites to drop, thus becoming a viable option in markets that were previously limited.

The combination of several characteristics distinguish the subject invention from other composite materials:

- ▶ It is a solid material that can be run without any lubricants,
- ▶ compatible with chemical and hostile environments,
- ▶ suitable in high-temperature applications ($> 400^{\circ}\text{F}$), and
- ▶ manufacturable in large sizes.

Because the identified markets are so broad in scope, two market niches were selected and the research was focused in these areas: (1) compressors utilized in industrial and residential applications, and (2) heat exchangers that operate in high-temperatures and hostile environments.

II. Technology Overview

Significant demand, driven by large defense and aviation spending in the 1980s, spurred research and development efforts in the area of high-performance composites. Researchers in universities, small private firms, and large corporations focused their energies on developing new materials. Because of these efforts, many new products were developed. Growth peaked in the mid-1980s at 25 percent per year. As defense spending decreased, composite producers were forced to refocus their efforts on alternative applications in order to remain in business. These applications included automotive parts, sporting goods, and medical equipment.

The subject invention is a method for making a composite material consisting of a vitreous carbon matrix containing convoluted fibers. The resulting product has better wear resistance, is tolerant of almost all hostile fluids and atmospheres, can be fabricated in large sizes without difficulty, and has a higher electrical conductivity than competing materials. Any of these characteristics can be optimized by choice of the fiber to be contained in the matrix and by properly adjusting the processing parameters.

III. Market Overview

The world carbon fiber composite market has been significantly impacted by the unstable U.S. economy. In the mid-1980s, growth had reached a peak of 25 percent per year, primarily the result of strong defense spending and high demand from the commercial aerospace industry. However, in the early 1990s, demand slowed to a growth rate of 8-9 percent and has further decreased to 6.2 percent per year. Unlike the 1980s, this growth is attributed to gains in the production of durable

goods and the extended use of composites in transportation (Chemical News Report, 1993). Additionally, process improvements and product innovations have allowed composite prices to drop, thus becoming a viable option in markets that were previously limited because of cost restrictions.

The passing of the North American Free Trade Agreement could create expanded opportunities. If industry experts' predictions are correct, a new record will be set in 1994 for total industry shipments. North American shipments of composites are expected to rise from 2.63 billion pounds in 1993 to 2.8 billion pounds in 1994. Steady production of durable goods, controlled inflation, low interest rates, stable oil prices, and expanding housing development are contributing factors in the increase, says a report from Owens-Corning (Chemical News Report, 1993). Additionally, as Latin American countries are adopting open-door economic policies, opportunities for growth are expected to significantly improve by 10.5 percent in 1994.

Since the late 1980s, U.S. composite manufacturers have been looking for new applications due to the decline in demand from the defense and aerospace markets, which is expected to decrease an estimated 6.8 percent in 1994. Commercial aircraft manufacturers are following the federal spending decline and delaying production orders. Aviation is the only market where an overall decline may occur in 1994.

Industries subject to high corrosion rates will drive the demand for composite reinforcements upward by 1.1 percent. An estimated 337 million-pound market in 1993, this increase is attributed to improvements in infrastructure resulting from substitution of glass-reinforced pipes for metal pipes (Chemical News Report, 1993).

The inventors of the subject invention have identified five initial target market niches for this invention: 1) railroad pantographs, 2) tip seals for rotary engines, 3) mechanical devices (seal plates, bushings, bearings, etc.), 4) heat exchangers, and 5) compressors. Because items 1 and 2 are relatively small industries with few manufacturers and item 3 is extremely large and broad, items 4 and 5 were chosen by the inventors to examine further. There may be other market niches suitable for this material because it can be fabricated in large sizes, but they have not been identified. The following sections, therefore, offer an analysis of the heat exchanger and compressor markets.

Compressors

In 1992, manufacturers' shipments of pumps and compressors totaled \$5.157 billion (16.4 million units), an increase of 1 percent from the 1991 figure of \$5.119 billion (15.7 million units). Industrial pumps accounted for 42.7 percent (\$2.2 billion), while compressors captured 40.3 percent (\$2.1 billion) of total domestic sales (U.S. Department of Commerce, 1992). These pumps and compressors are used in almost every major U.S. industry, ranging from heavy industrial applications to automobiles.

Industry contacts identified a high level of dissatisfaction with materials that are currently utilized in compressors, both in residential and commercial applications. A spokesperson for the Institute of Gas Technology (IGT), which is involved with the compressor industry, has been in contact with the inventors and has examined the subject invention. According to this individual, "The heating, ventilating, and air conditioning (HVAC) industry has a need and a desire to build non-lubricated compressors. This material's properties are very interesting if they can be proven in these applications." He also indicated that other high performance materials presently available are extremely expensive and not reliable.

Many key manufacturers in the compressor industry were contacted, such as Frick Company, Carrier, Sullair Refrigeration, and Trane Company. Manufacturers of products where the refrigerant was friendly to the compressor components, primarily in residential markets, were not interested in an advanced material. However, in many industrial applications (petro-chemical, pulp and paper, etc.), lubrication and wear of the components were a significant concern.

Sullair Refrigeration, with sales of \$100 million in the refrigeration industry, is a major producer of compressors used in residential and industrial applications. Ammonia is a primary refrigerant used in industrial applications and acts like a cleaning agent when in contact with seals and bearings. After the seals and bearings have extended contact with ammonia, the lubrication is removed, leaving metal on metal contact. An engineer from Sullair said that they currently use a thin film of oil to lubricate the seals. They have experienced substantial difficulty with keeping the seals lubricated, and they are currently looking for an alternative.

The Frick Company in Waynesboro, Pennsylvania, a manufacturer of screw compressors and rotary vane compressors used in the refrigeration industry, echoed similar remarks. The Frick Company has been looking for a material that is hostile-environment compatible. The refrigerant, ammonia-based R717, utilized in these compressors attacks the seal and bearing components. This spokesperson indicated that their search for new materials has lead them to PEEK plastics. This material has performed adequately; however, it "grows and expands" as it comes in contact with hostile chemicals and moisture. Because of this factor, the material must be machined to smaller dimensions, a tedious and expensive task.

Heat Exchangers

The total U.S. market in 1991, comprising all end-use sectors and all types of heat exchangers, amounted to \$1.66 billion. A study by Frost & Sullivan forecasts the total market will be more than \$1.9 billion in 1995. Additionally, the European heat exchanger market offers significant potential. Sales are expected to reach \$3.46 billion in 1994. Germany represents the largest single European market, with close to a quarter of the sales; however, the highest levels of growth will be in Ireland, Austria and Spain (Frost & Sullivan, 1992).

Heat exchangers are considered capital equipment, and, therefore, demand fluctuates with large capital expenditures. Heat exchangers are used in many different industries in all economic sectors of the U.S., including industrial, commercial, and residential (Frost & Sullivan, 1992). Over the short-term, however, the market can fluctuate as end-user industries make large investments in plant and equipment compared to periods of little capital expenditures.

Heat exchangers for most industries utilize materials such as aluminum, stainless steel, and titanium. These materials have adequate performance characteristics for low-temperature and non-corrosive environments. Industry representatives in these applications indicated that they are not pursuing new materials at this time. For example, a spokesperson from Brown Fintube Company, in Houston, Texas, said that they will only work with materials that are weldable. Composite materials offer solutions they do not need and at a higher cost.

A significant market niche for the subject invention was found where heat exchangers operate in high-temperature and hostile environments. These applications exist primarily in the chemical production industry and in certain applications within the petro-chemical industry. A spokesperson from Carborundum Company - Metallics Systems Division, a subsidiary of British Petroleum located in

Solon, Ohio, said that they are currently manufacturing and selling heat exchangers geared toward the high-corrosive chemical production industry.

This spokesperson indicated that there is strong competition among the companies that produce heat exchangers. Presently, approximately 15 companies produce heat exchangers for this environment. Total sales for this market niche is \$30 million from approximately 300 units and is experiencing slight growth. The Carborundum Company - Metallics Systems Division, a dominant manufacturer in this market, manufactures heat exchangers from two different materials. He indicated that if the subject invention performs as well as the inventors claim, it could provide his company with a significant competitive advantage.

Applications in high-temperature and hostile environments offer a relatively small market, but with high profit potential. Opportunities for the subject invention within the heat exchanger market may not be limited to this application as the technology is further developed. If performance factors outweigh the increase in cost, a significant opportunity may exist. It is also important to consider that market potential may exist in many other applications -- piston components, rotary pumps and engines, seals, bearings, rings, etc. These applications were not specifically examined because the subject invention has not proven it can be produced inexpensively enough to penetrate these markets.

IV. Competitive Environment

Research and development efforts in the area of composite materials are arduous and expensive tasks. Researchers, especially in smaller technology-driven firms, often develop materials without identified market demand or a market segment. Their primary goal is often to improve performance characteristics, such as increased wear resistance, improved impact-damage resistance, strength retention, etc. Applications are pursued after the fact and are often very difficult to match with desired performance characteristics.

Rensselaer Polytechnic Institute (RPI) in Troy, New York, in conjunction with General Electric Company's Research and Development Center, Ford Motor Company, and the National Institute of Standards and Technology, have been developing low- and intermediate-performance composites that are significantly less expensive than traditional composites. The research shows that low-performance composites could reach the market on a wide-scale basis within five years. The director of the composites center at RPI indicated that some are already being used in box beams behind auto bumpers. Once people become aware of the benefits of using composites, price will not be as major a concern (Farrell, 1992).

Currently in residential and most industrial applications requiring only moderate performance characteristics, manufacturers are using conventional materials (stainless steel, titanium, aluminum, etc.) and are basically satisfied. The benefits/advantages of the subject invention over conventional materials offer very appealing characteristics. However, according to a spokesperson from the Brown Fintube Company, industries using these conventional materials are conservative and resistant to change. For example, working with a material that is not welded would be a major change and, therefore difficult to incorporate. Additionally, cost considerations are of major concern. If the composite material is even slightly more expensive, it will be a hard sell.

Alternatively, companies that work with higher-priced pumps, compressors, and heat exchangers were very interested in the subject invention. The Carrier Corporation, manufacturer of residential and industrial HVAC systems, indicated that they have looked at ceramics, plastics, engineered plastics,

and a few composites. Currently, they have not found a material that could meet minimum performance characteristics; temperature always being the limiting factor. An engineer from this company said that if the material performs as the inventor claims and at temperatures in the 300 to 400°F range, the Carrier Corporation would be anxious to examine the subject invention.

Heat exchangers produced by the Carborundum Company - Metalics System Division are geared toward high-temperature and hostile environments, with primary applications in the chemical (including petro-chemical) production industry. These heat exchangers operate at a maximum temperature of 350°F and are constructed with two materials.

The first is an impervious graphite, which is resin treated. A spokesperson from this company said they produce this material internally and in its raw state costs \$150 per square foot of heat transfer surface. The subject invention is not sufficiently developed in order to make a cost comparison. The majority of the Metalics Division's sales are derived from this product. The second material is a silicon carbide that can withstand any type of corrosive chemical, but costs \$300 to \$400 per square foot of heat transfer surface. The spokesperson indicated that if this composite has the necessary performance characteristics and if it is less expensive, the Carborundum Company would be extremely interested.

Manufacturers that expressed an interest in utilizing advanced materials indicated they would need to thoroughly examine the product. The Frick Company in Waynesboro, Pennsylvania, indicated interest in the product, but the following steps would need to be completed.

- 1) Examination of a specifications sheet detailing performance characteristics and data,
- 2) Testing to determine the capability of component materials utilized with the subject invention,
- 3) Extensive cost analysis to determine factors such as alterations to the manufacturing process and raw material price,
- 4) Durability/accelerated life testing to determine expected life under specific situations, and
- 5) Negotiation of agreement between the invention's owners and the potential licensee.

V. Market Barriers

- A. Significant research and development efforts have focused on developing new composite materials. Attempts to commercialize these materials have been numerous leaving potential users often overwhelmed. This factor may identify the subject invention as "just another composite material."
- B. The subject invention's suitability for new applications is virtually unknown, because performance test data is unavailable for applied applications.
- C. Limited manufacturing capability may hinder the subject invention's ability to penetrate new markets.
- D. The general high cost of composite materials limits market applications.

VI. Keys To Success

- A. Development of a specification sheet detailing competitive advantages, performance properties, and product cost estimates will be crucial in order to educate potential customers.
- B. Qualified testing in specific environments will be necessary to prove the subject invention's suitability for applied markets.
- C. The establishment of a licensing agreement with a composite manufacturer will allow the inventors to meet potentially growing market demand.
- D. Further research into potential market niches will be necessary to successfully commercialize the subject invention.

VII. Summary & Conclusions

The subject invention appears to have significant potential in many markets. Significant interest was expressed by industry representatives within the two primary market niches examined. Given that the technology performs at levels claimed by the inventors, the heat exchanger market indicated especially strong interest. Due to the decline in defense and commercial-aviation spending, other markets less experienced with composite materials will need to be pursued. Emphasis on keeping the material inexpensive will be of primary concern in entering these new markets.

Because the subject invention's suitability for new applications is virtually unknown, qualified testing in specific environments will be necessary and expensive. Collaboration with private industry may be necessary to conduct this testing and also to manufacture the final product. Further research into these and other market niches will be necessary to successfully commercialize the subject invention.

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PROJECT REVIEW

To begin the market assessment process, the CIBD market assessment team reviewed copies of NIST evaluator Howard Robb's Final Technical Review, NIST consultant Dr. John M. Kennedy's Second-Stage Evaluation Report, and the submission made by the inventors, Ralph A. Burton and R. Gaines Burton.

These materials enabled us to initiate the database search conducted through Dialog Information Services. The search specialist accessed many different groups of databases organized by broad topic area. The topic areas were then narrowed to related areas which were investigated further. At this point, many resources were found directly relating to the topic of this assessment. Articles were found about trends in the development of advanced materials, and limited data about the overall composite market in the U.S.

Given the information the database search provided and information from the inventor, several key contacts were identified, as well as journals containing related information. This information provided contacts with the following:

- ▶ manufacturers of composite materials,
- ▶ potential users of the subject invention,
- ▶ trade and industry analysts and researchers, and
- ▶ academic instructors and researchers.

Subsequent phone calls within each group resulted in many discussions with industry experts. While conducting the phone interviews, individuals knowledgeable in this industry were easy to locate. This can be attributed to the considerable efforts to develop new advanced materials. Appendix A provides a list of the individuals who were able to assist in the assessment. These individuals, contacted by phone, proved to be the best source of information in accurately determining current industry trends.

In summary, the final market assessment is a result of a combined effort involving both primary and secondary research methods. Each research approach — database research, literature review, and personal conversations — contributed significantly to the final assessment. Phone conversations with industry experts resulted in the most accurate and timely information for determining the competitive products and also provided the most comprehensive market demand data. The research team is confident that the detailed research and the final report accurately portrays the current market potential for the subject invention.

APPENDIX C

Metal-Reinforced Carbon Composites[®]

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PREPRINT NO. 95-AM-7F-2
STLE PREPRINT

Exceptionally good friction and wear measurements are reported by permission of four national laboratories for materials designated MRCC (metal reinforced carbon composites). These versatile materials are made from a low-wear, non-graphitic carbon matrix with metal-fiber reinforcement. Counterfaces include austenitic and martensitic stainless steels as well as silicon nitride and alumina. The effects of high load, high temperature, and gaseous environments are reported.

The principal findings are:

1. Removal of humidity and atmospheric oxygen have little effect on friction and wear for MRCC sliding against a ceramic and a stainless steel.
2. Wear of aluminum oxide riders on MRCC is exceptionally low and not significantly affected by a broad range of contact loads.
3. Elevation of temperature to 260°C does not degrade the performance of 440-C riders on MRCC disks or raise friction significantly.

In small or large sizes the metal reinforced material is made in a single-pass process for approximately the same volume cost as cast iron. It is not limited by the diffusion processes characteristic of chemical vapor deposition. It is sufficiently rugged to survive heating in nitrogen well above the melting point of the fibers (1600°C) without loss of integrity or a major change of dimensions.

KEY WORDS

Carbon, Ceramic, Composites, Friction, Wear

INTRODUCTION

A versatile family of composites has been designated MRCC. The matrix, designated MRCC-0, is a form of non-graphitic carbon, containing small amounts of bonded hydrogen and hydroxyl groups. It was selected because it

showed extremely low wear and friction in dry sliding. When MRCC-0 was slid on MRCC-0, the friction coefficient varied around $\mu = 0.07$ and the wear factor was near to 10^{-8} mm³/N-m. This performance is close to that of lubricated contacts. For example, a brush operating at the sliding speed of 10 m/s, with 9.8 N normal load on a 1 cm² contact face would have a wear rate of only 0.31 mm/year. (Tests with current up to 30 amp/cm² showed no effect of current on wear, within the scatter of typical measurements.) Inclusion of continuous metal fiber provides a tough material that can be made in large sizes.

In a pilot study (1) it was found that friction and wear were dependent upon the counterface material and contact stress, but were not greatly affected by atmospheric oxygen and humidity. The MRCC did not exhibit "dusting" in dry, inert gas as graphitic materials would. This effect is of major significance, indicating that the mechanism of lubrication is not the same as that for graphitic carbon.

Dry sliding is emphasized here because it is the most severe contact condition and because MRCC provides unique opportunities for applications where lubricant cannot be used. At the same time, the materials respond well to lubricant and are compatible with liquid metals, oils, water and hostile fluids such as strong acids and bases. For coupons of the matrix material, weight change was less than the authors' limit of measurement, 10^{-4} , for immersion in hydrochloric acid (pH = 2) and sodium hydroxide (pH = 11) at 20°C for 200 hours.

The low wear rate and the atmospheric effects called for verification by independent laboratories with respected measurement systems and test techniques. The authors are grateful to those scientists who took an interest in the materials and incorporated a series of measurements into their experimental programs.

When the pilot study was published, MRCC was designated "glassy" or "vitreous" carbon, because the material is non-graphitic. This emphasis on a structural similarity to other pyrolytically formed hard carbons is now considered to be misleading. The materials were winnowed from a broad group of such carbons and should be considered unique.

The range of tribological behavior of pyrolytically formed carbons was pointed out by Dr. Paul Sutor, who summarized his own measurements on a range of "hard" carbons in a published discussion of Ref. (1). The differences among such materials are best delineated by measurements of the microstructure and chemical composition.

Vook et al. (2) have examined the matrix material with a broad range of physical techniques, and found it has an X-ray diffraction pattern similar to that of lampblack. This is markedly different from that of the vitreous carbon reported by Cowland and Lewis (3). Some H and OH were found to be firmly bound into the structure and not driven out by elevated temperature. The specimens had been baked in inert atmosphere for 24 hours at $T > 700^{\circ}\text{C}$.

The structural unit of the material was consistent with a hexagonal ring of carbon, and the crystallite size was found to be small (20 to $40\text{\AA}$). It was thought to be consistent with then postulated, but not yet isolated, fullerenes. Although the characterization does not explain the source of the excellent tribological performance, it serves to define the physical state of the MRCC matrix. Although the material contains almost spherical voids, X-ray scattering data showed little evidence of significant porosity.

In an effort to produce a highly conductive material for low-wear electrical brushes, copper alloy fiber was incorporated in amounts up to 85% or more by weight. These fibers were continuous (up to 1 meter in length) and approximately 0.1 mm in diameter. When the fibers were oriented randomly, the electrical and thermal conductivity fell within the range of commercial metal-filled carbon graphite materials. When aligned, resistivity along the favored axis ranged near $22\text{ }\mu\text{ohm-cm}$ for specimens with 10% volume fraction of copper. This is one decade lower than the resistivity with randomly placed fibers or infused metal. Thermal conductivity with random fiber orientation was $0.15\text{ W}/^{\circ}\text{C-cm}$. The flexural strength of a similar set of specimens with random fiber orientation was 34.56 MPa (4949 lb/in^2). The density was 2.44 g/cc or ≈ 0.11 volume fraction. Figure 1 is a photomicrograph of a typical cross-section. The modulus of elasticity was measured for a specimen with less metal content, ranging from 7 to 9.9 GPa , for a material strength of 13 MPa .

Fig. 1—Photomicrograph of MRCC, showing cross-sections of the metal fibers.

EFFECT OF ATMOSPHERE FOR METAL RUN AGAINST MRCC-0

In the pilot study (1) friction was shown to drop a small amount when laboratory air (50% R.H.) was displaced by dry nitrogen. This indicated a fundamental departure from the mechanism of lubrication of graphitic materials. At the same time questions could be raised as to possible effects of small impurities in the test chamber, and these could only be answered by measurements with stringent control of the environment.

Dr. Michael Dugger has carried out two sets of runs in dry air and in dry nitrogen. His rider was a pin of 440-C martensitic stainless steel (Rockwell C 60) with a tip radius of 0.79 mm, which was run on MRCC-0 disks. The contact load was 0.86 N. The specimens were operated for 500 cycles to establish steady state and the temperature was 35°C . Although the stainless steel was subjected to an elaborate preparation, the carbon specimens were not baked before testing. Table 1 summarizes the friction measurements.

A small rise in friction occurred upon replacement of the dry air by pure nitrogen. The measurements lie close to $\mu = 0.14$, as reported in Ref. (4) for 303 austenitic stainless steel pins on MRCC-0. These data support the conclusion that moisture or oxygen from the atmosphere are not required to maintain low friction when a metal is run against MRCC-0.

EFFECT OF ATMOSPHERE ON FRICTION AND WEAR OF Si_3N_4 ON MRCC-0

In the pilot study, silicon nitride was found to be a promising counterface when used either as the rider or the disk. For a silicon nitride rider sliding on MRCC-0, the friction coefficient was $\mu = 0.15$, and the wear factor for the silicon nitride ball was $W = 1.3 \times 10^{-9}\text{ mm}^3/\text{N-m}$. The wear of the carbon balls on silicon nitride disks was greater, averaging $\approx 5 \times 10^{-6}\text{ mm}^3/\text{N-m}$. The low wear of the silicon nitride riders was especially interesting when compared with similar tests of silicon carbide, which showed erratic friction and more than 10 times the wear rate. The promising results with the silicon nitride called for confirmation under stringently controlled test conditions.

Dr. Ali Erdmir has carried out tests in humid air, normal air, dry air, argon and nitrogen. Both the friction and wear factors were measured under moderately severe loading (2N load on a ball of 9.54 mm diameter) for a sliding distance of 165 m. The temperature varied around 28°C . Before testing, the specimens were rinsed in acetone and baked for 10 minutes in dry air at 100°C . These results are summarized in Table 2.

Again the effects of change of atmosphere on friction are found to be small. The wear measurements in the inert atmosphere group were around $W = 10^{-8}\text{ mm}^3/\text{N-m}$, which is comparable to that of MRCC-0 sliding on itself, the best combination discovered so far.

EFFECT OF LOAD ON WEAR OF A METAL AND CERAMIC ON MRCC-0

Dr. Peter Blau carried out a provocative set of measure-

Fig. 4—Dependence of friction coefficient on time (minutes) for MRCC riders on 440-C disks, operated in air at room temperature and elevated temperature.

less were both lower when the stainless steel was used for the rider than when it was used for the disk (1). The rider has a smaller metallic contact surface than the track on the disk; this surface is protected from open exposure to oxidation.

INTERPRETATION OF THE MEASUREMENTS

The combinations of metal content, counterfaces, loads, temperatures and atmospheres constitute a multi-dimensional system, for which any reasonable data set is only a sample. Nevertheless, consistencies between the present data and earlier studies indicate that some broad generalizations may be made safely.

In general, the best wear behavior is found for loads of approximately 1 N on the rounded specimens (≈ 1 cm diameter). When load was raised to 10 N, a significant increase in wear factor was found, although there was not a transition to a "severe wear" regime. There was no galling, scuffing or other form of surface distress in any of the variations of operating conditions. Figure 5 shows a photomicrograph of a typical wear spot on a rider, where the surface is mirror-like and the striations do not represent large departures from flatness, as evidenced by the absence of large serrations where they intersect the boundary of the spot.

The unexpected load-insensitivity for the wear factor of the aluminum oxide marks this counterface material as having promise for many applications.

Silicon nitride was singled out in earlier studies as a promising counterface, and its good performance is shown in Table 2 to be insensitive to atmospheric effects.

It is unfortunate that the temperature effects were measured for a pair that did not have a low wear factor, even at room temperature, at the high load chosen. Nevertheless, the smooth running, the lack of surface distress in the wear track, and the general level of performance indicate that elevated temperature does not produce a destructive effect on the interface.

When used with the preferred counterfaces, and in the best range of loads, this material family can provide ex-

Fig. 5—Typical wear scar on a rider, showing smooth, reflective worn surface surrounded by the unbroken surface of the MRCC-0 in the as-fired condition.

tremely good wear and friction results. Large excursions from ideal combinations will increase wear and friction. The systems are forgiving and there is no sense of operating in a narrow envelope of safe conditions.

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APPENDIX D

REPRESENTATIVE PROPERTIES:

For MRCC with approximately 57% by weight bronze alloy.

Specific gravity	2.7	g/cc
Hardness	124	Rockwell
Tensile strength	73.77 10,552	MPa psi
Specific heat	423	J/kg-°C
Thermal conductivity	0.25	W/cm-°C
Thermal expansion	7×10^{-6}	1/°C
Electrical resistivity	51	$\mu\text{ohm-cm}$