122
12/13/91 JS (2)

DOE/ID/12880-1
(DE92003050)

**DEVELOPMENT OF HIGH PERFORMANCE REFRACTORY FIBERS WITH
ENHANCED INSULATING PROPERTIES AND LONGER SERVICE LIFETIMES**

Phase I

**Enhanced Insulating Properties and Service Lifetime Proof-of-Principle
Demonstration**

Final Report

**By
P. C. Martin
G. L. DePoorter
D. R. Munoz**

February 1991

Work Performed Under Contract No. FC07-89ID12880

**For
U.S. Department of Energy
Office of Industrial Technologies
Washington, D.C.**

**By
Manville Sales Corporation
Denver, Colorado**

and

**Colorado School of Mines
Golden, Colorado**

DISCLAIMER

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, express 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.

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.

**DEVELOPMENT OF HIGH PERFORMANCE REFRACTORY FIBERS
WITH ENHANCED INSULATING PROPERTIES AND LONGER
SERVICE LIFETIMES**

PHASE I.

**ENHANCED INSULATING PROPERTIES AND SERVICE LIFETIME
PROOF-OF-PRINCIPLE DEMONSTRATION**

FINAL REPORT

February 1991

**P. C. Martin
G. L. DePoorter
D. R. Munoz**

Work Performed Under Cooperative Agreement DE-FC07-89ID12880

**Prepared for
U. S. Department of Energy
Idaho Operations Office, Idaho Falls, ID
Sponsored by the Office of the Assistant Secretary
for Conservation and Renewable Energy
Office of Industrial Technologies
Washington D.C.**

**Prepared by
Manville Sales Corporation
Corporate Technical Center
P. O. Box 5108
Denver, Colorado 80217-5108
and
Colorado School of Mines
Golden, Colorado 80401**

EXECUTIVE SUMMARY

The Manville Technical Center of the Manville Sales Corporation, Littleton, Colorado and the Metallurgical and Materials Engineering Department and the Engineering Department of the Colorado School of Mines, Golden, Colorado, under United States Department of Energy Cooperative Agreement No. DE-FC07-89ID12880, have initiated a three phase investigation of the development of high performance refractory fibers with enhanced insulating properties and longer usable lifetimes. This report presents the results of the first phase of the study, performed from August 1989 through February 1991, which shows that significant energy savings are possible through the use of high temperature insulating fibers that better retain their efficient insulating properties during the service lifetime of the fibers. The remaining phases of this program include the pilot scale development and then full scale production feasibility development and evaluation of enhanced high temperature refractory insulating fibers.

This first proof of principle phase of the program presents a summary of the current use patterns of refractory fibers, a laboratory evaluation of the high temperature performance characteristics of selected typical refractory fibers and an analysis of the potential energy savings through the use of enhanced refractory fibers.

The current use patterns of refractory fibers span a wide range of industries and high temperature furnaces within those industries. The majority of high temperature fiber applications are in furnaces operating between 2000 and 2600°F. The fibers used in furnaces operating within this range provide attractive thermal resistance and low thermal storage at reasonable cost. Higher temperature applications require significantly more expensive materials. The applications and analyses of the observed energy savings through the use of existing refractory fibers have been documented in the open literature and are included in the technology data base attached to this report.

A series of heat treatment studies performed for this phase of the program has shown that the refractory fibers, as initially manufactured, have attractive thermal conductivities for high temperature applications but the fibers go through rapid devitrification and subsequent crystal growth upon high temperature exposure. Exposure of the as-manufactured fibers to furnace temperatures well below the service temperatures of the fibers causes significant thermal conductivity and microstructural changes. These changes result in higher heat losses through the furnace walls and shortened fiber service lifetime because of the increased brittleness of the fibers.

Development of improved fibers, maintaining the favorable characteristics of the existing as-manufactured fibers, could save between 1 and 4% of the energy consumed in high temperature furnaces using refractory fibers. This savings is on the order of 0.01 to 0.03 quad Btu/y. These savings have been calculated based on models comparing furnaces insulated with existing fibers that degrade and furnaces insulated with the to be developed fiber(s) of this program.

The devitrification studies performed in Phase I indicate that the rate of crystalline phase development is quite rapid but possibly can be limited or suppressed sufficiently so that the fibers can retain the favorable characteristics of the vitreous as-manufactured fibers. Combining the proper refractory oxide phase compositions with properly controlled fiberization processes could result in new improved high temperature fibers. These potential compositions and processes will be explored in the subsequent phases of this program.

CONTENTS

	Page
EXECUTIVE SUMMARY	i
1. INTRODUCTION	1
1.1 Project Objectives	1
1.2 Summary of Phase I Tasks	2
1.3 Organization of Phase I Report	3
2. POTENTIAL ENERGY SAVINGS	4
2.1 Existing Energy Consumption Profile in Appropriate Industries	4
2.2 Furnace Configurations Modeled	6
2.3 Results of Energy Savings Calculations	7
2.4 Potential Energy Savings Compared to Savings Criteria	8
3. TECHNOLOGY SURVEY	9
3.1 Refractory Fiber Usage	9
3.2 Furnace Types	12
3.3 Devitrification of Refractory Insulating Fibers	12
3.4 Field Trips	13
4. SELECTION OF REPRESENTATIVE REFRACTORY INSULATING FIBERS FOR EVALUATION	15
4.1 Rationale for Fiber Selection	15
4.2 Purchase of Materials	15
5. THERMAL AND PHYSICAL PERFORMANCE AND CHARACTERIZATION OF SELECTED FIBERS	17
5.1 Test Sample Preparation	17
5.2 Heat Treatment	17
5.3 Shrinkage at 2600°F	18
5.4 Thermal Conductivity	20
5.5 Devitrification Studies	22
5.6 Significance of the Devitrification Studies	23

6.	ENERGY SAVINGS ANALYSIS	3 5
6.1	Selection of Furnaces for Modeling	3 5
6.2	Cylindrical and Box Batch Furnaces	3 5
6.3	Walking Beam, Rotary Hearth and Tunnel Kiln Continuous Duty Furnaces	3 9
6.4	Selection of the Computer Programs	4 0
6.5	Modification of the Computer Codes	4 3
6.6	Fiber Properties Used in the Modeling	4 3
6.7	Modeling Results	4 4
6.8	Energy Savings Calculation	4 5
7.	TECHNOLOGY SUMMARY	4 8
8.	REFERENCES	4 9
APPENDIX A.1		A.1.1
APPENDIX A.2		A.2.1
APPENDIX A.3		A.3.1
TABLES		
2.1	Energy Consumption in Appropriate Industries	5
2.2	Summary of Steady-State Furnace Wall Heat Loss Calculations	7
3.1	Industry, Applications, and Use Temperature for Refractory Insulating Fibers	1 0
3.2	Commercial Refractory Insulating Fibers Service Temperatures and Oxide Compositions	1 1
3.3	Industrial Heating Page Citations of Energy Savings Using Insulating Refractory Fibers, 1970-1989	1 2
3.4	Field Trips	1 3
4.1	Fibers Selected for Evaluation	1 6
5.1	Shrinkage at 2600°F	1 8
5.2	Apparent Thermal Conductivity at 1000°F Mean	2 1

5.3	Devitrification Products in the Five Selected Fibers Fully Devitrified and As-Received	2 3
5.4	Heating Times and Temperatures for Detailed Devitrification Study	3 0
5.5	Crystalline Phases in the Devitrification of Kaowool 2600	3 1
5.6	Crystalline Phases in the Devitrification of Kaowool ZR	3 2
5.7	Crystalline Phases in the Devitrification of Cerachrome	3 2
6.1	Operating Conditions for the Walking Beam Furnace in Three Zones	4 0
6.2	Temperature Set Point for Industrial Furnace Zones	4 0
6.3	Summary of Steady-State Furnace Wall Heat Loss Calculations ..	4 5
6.4	Energy Losses Through the Enhanced and Existing Fiber Wall in the Cylindrical Furnace	4 6

FIGURES

2.1	Typical Furnace Energy Flow	6
4.1	Refractory Fiber Usage by Application Temperature	1 6
5.1	Linear Shrinkage of Fiber Felts Heat Treated at 2600°F	1 9
5.2	Thermal Conductivity of Fiber Felts Heat Treated at 2600°F	2 2
5.3	X-Ray Diffraction Patterns for Kaowool ZR at Various Heat Treatment Times at 2600°F	2 4
5.4	SEM Views of Kaowool ZR at Various Heat Treatment Times at 2600°F	2 6
5.5	Amorphous Residual During Devitrification of Kaowool 2600 ..	3 3
5.6	Amorphous Residual During Devitrification of Kaowool ZR	3 3
5.7	Amorphous Residual During Devitrification of Cerachrome	3 4
6.1	Cylindrical Furnace Model	3 6
6.2	Typical Walking Beam Furnace	3 7
6.3	Typical Rotary Hearth Furnace	3 8
6.4	Typical Tunnel Kiln Section	3 9
6.5	Comparison of DOT and TOPAZ Codes, Cold-Side	4 2
6.6	Comparison of DOT and TOPAZ Codes, Wall Mid-Plane	4 2

DEVELOPMENT OF HIGH PERFORMANCE REFRACTORY FIBERS WITH ENHANCED INSULATING PROPERTIES AND LONGER SERVICE LIFETIMES

PHASE I: ENHANCED INSULATING PROPERTIES AND SERVICE LIFETIME PROOF-OF-PRINCIPLE DEMONSTRATION

1. INTRODUCTION

1.1 Project Objectives

The overall objective of this research project (under Cooperative Agreement N0. DE-FC07-89ID12880) is the development of improved high performance refractory fibers with enhanced insulating properties and longer service lifetimes. Included is:

- The exploitation of a more complete silica, alumina, and zirconia ternary phase diagram
- The assessment of current technology, including the development of a data base of existing fibers application in the glass, aluminum, cement, iron, and steel industries.
- The development of new fibers with the goals of higher service temperatures, lower shrinkage during use, improved long-term thermal properties, increased lifetime projections, and better understood and controlled properties
- The production and testing of new fibers at pilot and full plant scales
- The assessment of the energy and cost savings attainable through the development of improved fibers
- The transfer of research results to industry.

Titles of each of the phases and corresponding objectives are listed as:

Phase I: Enhanced Insulating Property and Service Lifetime Proof-of-Principle

To assess the current technology and use patterns of existing refractory fibers, to establish a data base on currently used refractory fibers, and to develop an estimate of the potentially attainable energy savings as a result of developing enhanced insulating property and service lifetime fibers.

Phase II: Improved Refractory Fiber and Industrial Benefit Development

To develop new refractory fiber compositions, to expand the data base under development, produce new fibers at pilot-scale, evaluate the production methods and produced fibers, and select candidate fiber compositions for subsequent full-scale production and industrial tests.

Phase III: Pre-Commercialization of Technology

To evaluate full-scale production of improved fibers, perform full-scale industrial tests, evaluate the characteristics of improved refractory fibers, continue assessments of industrial interest in the benefits of improved refractory fibers, finalize the energy and cost savings analyses, and to transfer the results of this research to industry.

1.2 Summary of Phase I Tasks

Task 1 - Develop Existing Technology Database

A data base shall be developed, using data acquired by way of a literature search and survey of refractory fiber users in high volume end-use industries such as iron and steel, glass, cement, and aluminium. The data base shall be used for the determination of potential thermal energy savings.

Task 2 - Select Fibers for Evaluation

Refractory fibers shall be selected, from those identified in Task 1, for sample characterization, and thermal property determination.

Task 3 - Determine Thermal Properties

Determine the thermal conductivity of insulating materials produced from the selected fibers, as-manufactured and as thermally treated, at operating and extreme temperatures.

Task 4 - Perform Sample Characterization

Characterize the structure, volume changes, and phase transformations of the selected fibers, as-manufactured and as thermally treated, at operating and extreme temperatures. The characterization data will be correlated with the thermal property data and all data will become part of the database under development.

Task 5 - Estimate Energy Savings

Energy savings shall be estimated by comparing the data assembled in this phase of the project with that potentially achievable from the development of enhanced insulating property and service lifetime fibers. The estimate shall be reviewed with the Department of Energy (DOE), and no further research will be performed if a potential energy savings of 0.01 quad Btu/y is not achievable.

Task 6 - Provide Phase I Report

1.3 Organization of Phase I Report

For reporting purposes, the results of Phase I will be reported in a different order than the tasks summarized above. The results will be presented as follows:

Potential Energy Savings: The potential energy savings resulting from the usage of improved refractory fibers will be described using the results of information obtained during this study. The basis of the calculations of the energy savings will be described in further detail in the section on Energy Savings Analysis.

Technology Survey: The technology survey includes information gained from:

1. A search of open literature on typical furnaces, insulation properties, material properties, and furnace models
2. Field trips to industrial users of refractory fibers
3. A review of available manufacturer's literature
4. Government documents
5. Private communications with users, furnace manufacturers, and others.

Selection of Representative Refractory Insulating Fibers for Evaluation: The criteria for fiber selection and the acquiring of the selected fibers is described.

Thermal and Physical Performance and Characterization of Selected Fibers: The thermal treatment and resulting tests of thermal performance and physical characterization of the fibers are described. The results of the tests on the fibers has become the basis for the energy savings analysis and an indication of direction for improving the thermal performance of refractory fibers.

Energy Savings Analysis: Further details of the calculation of energy losses in typical furnaces is given. This analysis is the basis for the demonstration of at least 0.01 quad Rtu/y potential energy savings.

Technology Summary (Data base): The accumulation of pertinent data is presented as the technology summary.

2. POTENTIAL ENERGY SAVINGS

2.1 Existing Energy Consumption Profile in Appropriate Industries

Appropriate industries are defined as those industries where use of refractory fiber insulating materials is feasible. Conditions where use of refractory fiber is not feasible can be broken into two categories; (a) furnace linings exposed to severe corrosive chemical environments such as those common in the aluminum, glass, cement, and chemical industries and (b) in situations where mechanical abrasion is present, such as the hearth, floor, traveling car or any part of the furnace that must support the product load in both continuous or batch processes.

A search for detailed energy consumption data focused on the primary metal reheat, ferrous metal heat treating and ceramic heating processes. The energy consumption in these processes provides the most conservative estimate of potential energy savings when using an improved refractory fiber over fibers that are commercially available. An excellent source of information was found in a report to the Gas Research Institute (GRI) by McDermott and Chapman (1988). The energy consumption data published in this report are subdivided into categories that are consistent with appropriate industrial processes for this study. These energy consumption data were verified by other reports including another GRI report (Koch, McDermott and Klareich, 1987) and a DOE report published by the Energy Information Administration (EIA) (1988). In addition, contacts were made in person with local manufacturers of steel (Riley and Ellers, 1990; Moore and Walker, 1989) and clay brick products (Stumpff, 1989) and by phone conversations with several major aluminum (Lippert, 1990, Jacobs, 1990, and Sterahan, 1990) and steel (Christiansen, 1989) industries.

Because it has been difficult to specifically identify the fraction of the Chemical and Allied Products and Petroleum and Coal Products industrial processes that can be characterized as having corrosive environments, these were left out of the primary energy savings calculation. However, there may indeed be applications within these industries where refractory fiber use is feasible and future efforts should be made to estimate the potential energy savings in this category. Additionally, it is unnecessary to include the energy consumption in these industries to show that 0.01 quad of energy could be saved with the development of an improved refractory fiber.

The energy consumption data utilized for this study are summarized below in Table 2.1. The furnace fuel types are broken into two categories; electrically heated and natural gas and other fuels. The sum of the electrical energy column was divided by 0.34, which represents the

efficiency of converting the electricity from another fuel (such as fossil, nuclear, hydroelectric or solar), then added to the sum of furnace thermal energy provided by natural gas or other fuels. As shown in Table 2.1, it is estimated that in 1985, 0.7035 quad of energy were consumed in industries deemed appropriate for this study.

Several articles were found that provided energy flow (Sankey) diagrams for various furnace configurations (Casana and Stabile, 1983, Hollander and IJmuiden, 1983, Molloy, 1985, and Visakanta and Menguc, 1987). A typical energy flow diagram is provided in Figure 2.1. In addition, the GRI report by Koch, (1987) provides detailed furnace energy balance information on batch and continuous furnaces used in the ferrous metal heat treating industries.

As shown in Figure 2.1, the flow of energy out of the furnace is typically divided into three portions. The largest fraction, 30 to 50% of the energy input generally is lost through the flue. Typically 30 to 35% of the energy input will leave with the product. The remainder (10 to 20%) of the energy will exit through the furnace walls in steady-state operation or is lost through energy storage in the batch processes. Therefore, a range of from 10 to 20% of the energy input to the furnace is used to estimate the wall energy losses for furnaces typical of the industries that use refractory fiber insulation.

Table 2.1 Energy Consumption in Appropriate Industries

PROCESS	Energy Consumption (10^{12} BTU)		
	Electrical	Gas + Other	Total
Steel Reheat	1.9	171.2	173.1
Steel Soaking Pit	0.0	45.1	45.1
Ferrous + Nonferrous Forging	1.6	20.1	21.7
Atmosphere Generation (Exo+Endothermic)	0.0	39.0	39.0
Aluminum Heating	3.2	12.6	15.8
Ferrous Metal Heat Treating	42.2	165.6	207.8
Copper Heat Treating	1.5	6.1	7.6
Brick and Structure Clay Tile	0.0	48.4	48.4
Refractories	0.0	7.2	7.2
Structural Clay Products	0.0	2.7	2.7
Ceramic Wall + Floor Tile	0.0	6.8	6.8
Aluminum Anode Baking	0.0	7.7	7.7
Agglomeration / Sintering (Iron Ore)	0.0	22.8	22.8
Totals (* indicate 34% efficiency for electrical energy production)	50.4 148.2*	555.3	605.7 703.5

Figure 2.1 Typical Furnace Energy Flow

2.2 Furnace Configurations Modeled

This section provides a summary of the modeled furnaces. More detailed information can be found in Subsection 6.2. One batch furnace and three continuous duty furnaces were modeled. Because the computer codes were limited to two-dimensional calculation domains, only the axisymmetric or cylindrical (bell type) batch furnace was modeled numerically. However, hand calculations were performed for the steady state heat losses from a box furnace and are compared with the results from the cylindrical furnace model in Subsection 6.2.

Three continuous duty furnaces were also modeled and are listed as follows:

1. Tunnel kiln, with rectangular vertical cross section, used for firing clay brick, refractories, and whitewares
2. Walking beam furnace (similar to the tunnel kiln), with rectangular vertical cross section and a moving beam mechanism to propel the product through the furnace, used to reheat steel or nonferrous metals
3. Rotary hearth furnace, with rectangular vertical cross section but toroidal horizontal cross-section, also used to reheat metal and fire ceramics.

2.3 Results of Energy Savings Calculations

The results of the energy savings calculations are provided in tabular form in this section. Properties of the existing refractory fibers were determined by the measurements of bulk thermal conductivity and shrinkage as described in Section 5. These are the in-service properties of the commercially available fibers. After the heating of the fibers as a result of being used in a furnace, the fibers show devitrification and consequently have increased thermal conductivity and are more brittle than the as-received fiber. The properties of the enhanced refractory fiber were assumed to be those of the as-received commercial fibers, representative of the properties of an improved or enhanced fiber. The thermal conductivities of the as-received fibers were measured using the same techniques used for the heat treated fibers, as indicated in Section 5. The steady state results of the energy savings calculations are summarized below in Table 2.2. In general, 11 to 19% of the thermal energy transported through the furnace wall can be saved when a fiber that does not devitrify (enhanced) is used in place of commercially available, that is, existing refractory fibers that have experienced heat treatment.

Results of the heat storage from the transient analyses of the cylindrical batch furnace were not included here because there is only a small difference in energy savings, ~4%, when an enhanced fiber is used in place of an existing fiber. Also, it was assumed in this transient analysis that the furnace was completely cooled to standard ambient air temperature. Complete cooling is an unrealistic assumption for most industrial applications unless the furnace is being rebuilt (according to Koch, 1987, this may occur only once every several years, depending on the particular process). Uncertainty in the temperature to which the furnace is cooled between batch cycles added to the reasons for not considering the heat storage terms in the energy savings calculations.

Table 2.2 Summary of Steady-State Furnace Wall Heat Loss Calculations

FURNACE TYPE	Wall Heat Loss (BTU/day)		ENERGY SAVINGS, (%)
	Existing Fiber	Enhanced Fiber	
Cylindrical (Batch)	2.049×10^7	1.655×10^7	19.2
Walking Beam (Continuous)	2.179×10^6	1.841×10^6	15.5
Rotary Hearth (Continuous)	2.640×10^8	2.353×10^8	10.9
Tunnel Kiln (Continuous)	3.842×10^6	3.126×10^6	18.6

2.4 Potential Energy Savings Compared to Savings Criteria

Potential energy savings are calculated using each portion of information summarized above. It is known that 10 to 20% of the energy input to the furnace passes through the wall and that 11 to 19% of this wall loss can be conserved by using an improved fiber. The product of these percentages yields the fraction of energy that potentially can be saved when the improved refractory fiber is used in the appropriate industrial process. Therefore, 1.1 to 3.8% of the energy consumed (0.7035 quad in 1985) yields 0.0077 to 0.027 quad of energy saved. The criterion for this study was to show that 0.01 quad potentially could be saved if an improved refractory fiber were developed to replace commercially available refractory fibers. The average potential energy savings is 0.017 quad, 70% larger than the criterion.

There are enormous potential energy savings in the conservative listing of processes shown in Table 2.1. However, figures from the EIA report for the Department of Energy (1988) also provide general energy consumption data for the Chemicals and Allied Products (3.567 quad) and the Petroleum and Coal Products (5.123 quad) industries. These industries may also include processes where there is potential for substantial energy savings through the use of refractory fibers. Further detailed analysis will be required to provide a conservative list similar to that of Table 2.1. However, if it is assumed that 50% of the energy consumed in these industries is related to high temperature processes (500 to 1500°C), if 10% of this energy flows through the process container walls, and if 10% of this energy can be saved through use of an improved refractory fiber then an additional 0.044 quad potentially could be saved annually.

3. TECHNOLOGY SURVEY

Industrial heating applications that currently use refractory insulating fibers were surveyed to provide a basis for the calculation of energy savings that could be realized if improved refractory fibers were developed. The utilization of the improved fibers would be limited to furnaces where refractory insulating fibers are currently being used or potentially could be used. Specific examples of energy savings by using refractory insulating fibers were also documented. The technical literature was surveyed to find information on the behavior of refractory fibers subjected to heat treatment.

Computer assisted literature searches were performed in the SHE Engineering Index, Compendex Plus, and Chemical Abstracts. Compendex Plus and the SHE Engineering Index were searched for information on furnaces, furnace design, fiber utilization in furnaces, fiber properties, and energy savings because of using refractory insulating fibers. Chemical Abstracts was searched for technical information on the devitrification (recrystallization) of alumino-silicate fibers. A complete listing of the references found including title, literature citation, and general subject area is included in Appendix A.1.

3.1 Refractory Fiber Usage

Industries, applications within industries, and use temperatures of refractory insulating fibers are summarized in Table 3.1. Commercial refractory insulating fibers, their service temperatures, oxide compositions, and manufacturers are summarized in Table 3.2. Note that the refractory insulating fibers are divided into fibers that are vitreous or amorphous as manufactured and fibers that are polycrystalline as manufactured.

Refractory fiber insulation is a recommended and accepted material for industrial furnaces. A study sponsored by the Gas Research Institute (Kerfer 1986) recommends that some form of fiber insulation should be given serious consideration for all furnaces. This recommendation is based on experimental studies of furnaces. The GRI study:

1. Describes insulating fiber compositions, manufacturers, and service temperatures
2. Shows typical applications
3. Describes the installation options
4. Lists a series of Do's and Don'ts for refractory fiber usage
5. Describes several case studies.

Many specific instances of reported energy savings by using refractory insulating fibers have been reported in the literature. For example, during the time period from 1970 through 1989, 78 articles appeared in Industrial Heating reporting documented energy savings by using refractory fibers. Table 3.3 details the specific references to these articles by year, month and page.

The widespread industrial use of refractory insulating fibers and the documented energy savings by using refractory insulating fibers have been illustrated in Tables 3.1 and 3.2. Therefore, there is potential for even more energy savings if an improved refractory fiber could be developed and produced.

Table 3.1 Industry, Application, and Use Temperature for Refractory Insulating Fibers

INDUSTRY	APPLICATION	TEMPERATURE (°F)
Industrial inorganic chemicals	Heater and reformer linings Catalyst filter	2200 to 2600 2300
Agricultural chemicals	Lining of hot-gas ducts	2000 to 2300
Petroleum refining	Heater and reformer linings	2200 to 2600
Glass	Glass tank crowns Regenerator walls Dog house	? 2300 2300
Ceramic	Kiln linings Low-mass kiln cars Kiln car seals	2200 to 2600 2300 2300
Iron and steel	Soaking pit cover seals Reheat furnaces Tundish cover seal Coreless induction furnace Forge furnaces	2300 2200 to 2600 2000 to 2300 2300 2200 to 2600
Nonferrous metals	Reheat furnaces Soaking pit cover seals Coreless induction furnaces Heat treating furnaces Tundish cover seals Forge furnaces	2200 to 2600 2300 2300 1800 to 2600 2000 to 2300 2200 to 2600

Table 3.2 Commercial Refractory Insulating Fibers Service Temperatures and Oxide Compositions

A. As-Manufactured Vitreous Fibers

SERVICE (°F)	MANUFACTURER	PRODUCT TRADE NAME	OXIDE COMPOSITION (Wt%)			
			Al	Si	Zr	Cr
1400	Carborundum	Fibermat	?	?	—	—
1600	Manville	Cerawool Blanket	40	50	—	—
1800	Carborundum Thermal Ceramics	Duraback	40	57	—	—
		Blanket B	44	50	—	—
		Kaowool Wet Felt	?	?	—	—
1900	Thermal Ceramics	Pyro-Bloc E	47	53	—	—
2000	Carborundum Thermal Ceramics	Moist-Pack D	35	63	—	—
		Kaowool Bulk A,D,C	45	53	—	—
		Blanket	49	51	—	—
2150	Thermal Ceramics	HP Blanket, HP Fiber	47	53	—	—
		Pyro-Log R Grade Fiber	47	53	—	—
2200	Carborundum Thermal Ceramics	Anchor-Loc 2200, Bonded 22	40	52	5	—
		Pyro-Bloc Y/T-Bar Y:R	47	53	—	—
		Unibloc/Saber Bloc II: HP	47	53	—	—
2300	Carborundum	Durablanket, HP-S	40	52	5	—
		KTMX Fiber	43	54	—	—
		Long Staple Fiber, PH Blanket	44	51	5	—
		Spun Bulk, Durablanket HP-S	45	55	—	—
		Durablanket	46	51	—	—
		Regular Bulk, Lo-Con Felt	49	51	—	—
	Thermal Ceramics	2600 Blanket	49	51	—	—
2400	Thermal Ceramics	Pyro-Log ZR Grade Fiber	32	48	20	—
		ZR Blanket, ZR Fiber	34	46	20	—
	Carborundum	Anchor-Loc 2400, Bonded 24	45	55	—	—
	Manville	Cerablanket, Cerafiber	47	53	—	—
2500	Thermal Ceramics	Pyro-Bloc Y/T-Bar Y:ZR	32	48	—	—
		Unibloc/Saber Bloc II: ZR	32	48	20	—
2550	Manville	Cerachem	?	?	?	—
2600	Carborundum	Anchor-Loc 2600, Bonded 2600	30.5	53.5	16	—
		Durablanket 2600	30.5	53.5	16	—
	Manville	Cerachrome Blanket, Felt	43	55	—	2.5
2700	Thermal Ceramics	Pyro-Bloc Plus: Cr	66	32	—	2
2800	Carborundum	Bonded 30	75	23	—	—

B. As-Manufactured Polycrystalline Fibers

SERVICE (°F)	MANUFACTURER	PRODUCT TRADE NAME	OXIDE COMPOSITION (Wt%)			
			Al	Si	Zr	Cr
2800	Thermal Ceramics	Saffil, Bilk, Kaowool HT	96	4	—	—
		Saber Bloc II	96	4	—	—
		Unifelt 300 (HT)	<96	>4	—	—
2900	Thermal Ceramics	Unifelt XT	<96	>4	—	—
3000	Carborundum	Fibermax Bulk Fiber, Mat	72	37	—	—

Table 3.3 Industrial Heating Page Citations of Energy Savings Using Insulating Refractory Fibers, 1970 to 1989

MONTH YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1970	122											
71									1789	2014		
72									1790	1905		
73			505		905	1097				1855	57	
74				58	74				81			
75									67		75	59
76			58	33			50		54	52		
77				14	47			36				
78				20	38			42				37
79			32	18		47	41		46	36,38		
1980	34			63	44			41	37,38			
81				24,29		42					42	
82	39			12,17		54	38		38	43		22
83			30,32				12,15		46			
84				28,34 38			31,34			46	42	
85			24	55			36	41				
86				20							52	
87											24,28	35
88				28,34		23						
89				43								

3.2 Furnace Types

Several examples of furnace type are illustrated in the Gas Research Institute (GRI) Report mentioned above. In addition, natural gas fueled furnaces are described in detail in another GRI report (Koch, 1987). The furnace configurations used for the energy savings analysis in this report are described in Section 6.

3.3 Devitrification of Refractory Insulating Fibers

Refractory insulating fibers are installed in two different physical states, vitreous and polycrystalline. The vitreous fibers are more widely used and generally less expensive than the polycrystalline fibers. However, the vitreous fibers are known to shrink and become brittle during use. This shrinkage and brittleness result from initially vitreous or amorphous fiber devitrifying or becoming crystalline upon exposure to heat at typical furnace operating temperatures.

Several experimental studies of the devitrification or recrystallization of alumino-silicate refractory fibers have been reported. The shrinkage has been associated with the devitrification or

recrystallization of the fibers. However, none of these studies report measuring the thermal conductivity of the fibers as a function of heat treatment.

The results of these studies are summarized as follows. For vitreous fibers containing only alumina (Al_2O_3) and silica (SiO_2), mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) begins to crystallize at about 1000°C with cristobalite appearing at temperatures of about 1300°C (Ganz and Kronert 1982, Courier, 1982, Gaodu, 1977). The addition of chromia (Cr_2O_3) increased the thermal resistance of the fiber (Schulle, 1986). The results of these studies are summarized in detail in the work of Lo (1991).

3.4 Field Trips

Plant visits were made to several facilities where refractory insulating fibers are being used. These included a brick manufacturing plant, a modern ceramics production facility, a steel producing plant, and a brass production facility. Other manufacturers were contacted by telephone. Other technical people with experience in using refractory insulating fibers were also contacted. The information obtained from these visits is summarized in Table 3.4. These plant visits and personal contacts were conducted in the beginning of the project. The information obtained was utilized in the selection of typical furnaces for modeling and other factors in the energy savings calculations.

Table 3.4 Field Trips

A. Plant Facilities Visited

Company Product	Relevant Information Obtained
Brick	Furnace Type: Tunnel kiln. Very little fibrous insulation is currently being used at this location, however another local brick manufacturer uses fibrous modules throughout their furnaces. Industry concern is with furnace thermal stability and maintenance cost.
Ceramics	Furnace Type: Variety of hearth furnaces and trolley and rotary kilns. Use fibrous insulating materials to fill gaps between the refractory brick, some use in walls and ceiling but primary use is refractory brick. Major concern with fiber usage is mechanical abrasion and lifetime. Not as concerned with energy savings.
Steel	Furnace Type: Rotary reheat, walking beam reheat furnaces and ladle covers. Currently use fibrous modules in the ceiling of the rotary kiln, throughout the walking beam furnace and on the ladle covers. Concerned with accidental mechanical damage of fibrous insulating materials in other high temperature steel making processes.
Brass	Furnace Type: Large rectangular and rotary reheat furnace. Fibrous insulation is used in the large rectangular reheat furnace and in the ceiling of the rotary reheat furnace. Though not currently utilized, it could also be used on the ladle covers.

B. Interviews with Manufacturers

Company Name	Relevant Information Obtained
Geneva Steel	They have several coke furnaces (2200 to 2400°F), a blast furnace (2500 to 2600°F) and an open hearth furnace (2800° to 3000°F).
Kaiser Aluminum	Low density fiber currently used in roof of top charged melting furnaces (2100 to 2500°F). Other possible applications; top loading homogenizing furnaces (1000 to 1100°F) and annealing furnaces (800 to 900°F).

C. Interviews with Technical Resource People

Person	Relevant Information Obtained
President, Refractory Sales Company	Applications for refractory insulating fibers. Fiber condition after usage. Contacts in the industries using fiber insulation.
Steel Plant Refractories Engineer	Applications for refractory fibers in Steel Plant Description of fiber conditions after continuous use.

4. SELECTION OF REPRESENTATIVE REFRACTORY INSULATING FIBERS FOR EVALUATION

4.1 Rationale for Fiber Selection

The continuous operating temperatures, trade names, manufacturers, and chemical compositions of the refractory fibers currently in use are shown in Table 3.2 of Section 3. All of these fibers contain alumina (Al_2O_3) and silica (SiO_2). Some fibers have significant amounts of either chromia (Cr_2O_3) or zirconia (ZrO_2). Trace amounts of other oxides are not considered here. Some fibers are polycrystalline as received and some fibers are vitreous as received. There is a general, but not exact, correlation of continuous service temperature with alumina content for fibers containing only alumina and silica. The polycrystalline fibers have higher continuous service temperatures than the vitreous fibers. Therefore, fibers were examined over a range of alumina and silica contents. Additions of either chromia or zirconia to the fibers appears to increase the continuous useful temperature above that which would be expected based on the alumina/silica ratio. Therefore, the effects of additions of either chromia or zirconia were investigated.

The specific compositions chosen (therefore the continuous service temperatures) should represent fibers that are widely used that are either costly to replace or are at the extreme of fiber use temperatures. The distribution of refractory fiber applications with specified continuous service temperatures is shown in Figure 4.1. The majority of applications are for fibers with continuous service temperatures of between 2300 and 2400°F. Therefore, two fibers were chosen with this continuous service temperature. One, Kaowool 2600, contains only alumina and silica and the other, Kaowool ZR, contains alumina, silica, and zirconia. A fiber with a 2600°F continuous service temperature, Cerachrome, was chosen because it contains alumina, silica, and chromia. The two highest continuous service temperature fibers at 2800°F, Saffil Alumina, and 3000°F, Fibermax, were chosen because developing a higher continuous service temperature fiber is one of the objectives of this project. Fiber names, compositions, and continuous service temperatures for the selected fibers are shown in Table 4.1.

4.2 Purchase of Materials

One box each of the Saffil Alumina, Fibermax, Kaowool 2600, and Kaowool ZR was purchased from a local distributor. The Cerachrome was obtained directly from Manville.

Figure 4.1 Refractory Fiber Usage by Application Temperature

Table 4.1 Fibers Selected for Evaluation

FIBER	COMPOSITION, Oxides of				Continuous use Temperature (°F)
	Al	Si	Zr	Cr	
Kaowool 2600 (Vitreous)	52	48	--	--	2300
Kaowool ZR (Vitreous)	34	46	20	--	2400
Cerachrome (Vitreous)	42.5	55	--	2.5	2600
Saffil Alumina (Polycrystalline)	96	4	--	--	2800
Fibermax (Polycrystalline)	72	27	--	--	3000

5. THERMAL AND PHYSICAL PERFORMANCE AND CHARACTERIZATION OF SELECTED FIBERS

The five fibers selected for evaluation were all heat treated at a constant temperature for controlled time periods and measured for thermal and physical characteristics. The test samples were prepared so that the shrinkage or dimensional changes and the thermal conductivity could be measured on the same piece. Crystalline phase composition by x-ray diffraction analysis and the microstructural analysis by electron microscopy were performed on smaller companion pieces, heat treated at the same time as the larger thermal conductivity samples.

The heat treatment temperature was set at 2600°F for all five materials. The heat treatment times initially chosen were 4 h and 24 h. After the evaluation of the fibers at these initial test times, an additional heat treatment was conducted for 168 h (7 d).

5.1 Test Sample Preparation

Three fibers, Kaowool 2600, Kaowool ZR, and the Cerachrome, were received in blanket form (nominal 8 lb/ft³, 1 in. thick). Because the thermal conductivity of refractory fiber blankets is related to the density of the blanket, similar density test pieces were obtained by cutting the blanket into a number of 12 x 12 in. pieces. The samples to be tested were selected by picking pieces within 5 g of the same weight. The companion pieces for x-ray and microscopy were cut 3 x 2 in. from the blanket near the same area as the large samples.

Two fibers, Fibermax and Saffil, were received in bulk form. Similar density samples of each fiber were prepared for the thermal treatments by dispersing 410 g of fiber and 8 g of cooked starch in 4 gal of water. The mixture was dewatered by free-draining in a 14 x 14 in. board former. The formed wet board was pressed to 1 in. thick and dried. The dried boards were trimmed to 12 x 12 in. for the thermal conductivity testing and the edge trim was saved for heat treatment for the x-ray and microscopic evaluations.

5.2 Heat Treatment

Each 12 x 12 in. fiber sample, along with a companion 3 x 2 in. piece, was placed in a preheated, electrically heated furnace. The furnace temperature was controlled at a set point temperature of 2600°F. Each sample set was placed in the furnace for one of the set times of 4 h, 24 h, or 168 h. One set of samples was retained with no heat treatment for as-received evaluations. The 4 and 24 h samples were heat treated before being tested for thermal and physical characteristics. After these samples and the as-received samples were evaluated, additional samples were heat treated at 168 h and evaluated.

5.3 Shrinkage at 2600°F

The physical dimensions of each test sample were measured before and after heat treatment at 2600°F. The shrinkage of each fiber blanket was determined by comparing the before and after measurements. The shrinkage results are plotted in Figure 5.1, where the length and width shrinkages are averaged, and shown in Table 5.1. The major portion of the shrinkage occurred within the first four hours of heat treatment. The two higher temperature fibers, Fibermax and Saffil, exhibited the lowest extent of shrinkage, of ~2%. The three other fibers, Kaowool 2600, Kaowool ZR, and Cerachrome exhibited more shrinkage, up to 12%. The 12 x 12 in. heat treated test samples were retained for thermal conductivity testing. The 3 x 2 in. heat treated test samples were retained for x-ray diffraction and electron microscopic evaluation.

Figure 5.1 Linear Shrinkage of Fiber Felts Heat Treated at 2600°F

Table 5.1 Shrinkage at 2600°F

SAMPLE	AS RECEIVED					FIRED					SHRINKAGE		
	WEIGHT gm	WIDTH Inches	LENGTH Inches	THICK Inches	DENSITY pcf	WEIGHT gm	WIDTH Inches	LENGTH Inches	THICK Inches	DENSITY pcf	WIDTH %	LENGTH %	THICK %
KAOWOOL 2600 AS RECEIVED 4 HOURS @ 2600°F 24 HOURS @ 2600°F 168 HOURS @ 2600°F		12.05	12.12	1.10		330.0	10.85	11.11	0.93	11.20	9.8	8.4	15.5
	330.7	12.03	12.13	1.10	7.84	329.4	10.40	10.98	0.95	11.56	11.3	8.6	9.5
	329.6	11.72	12.01	1.05	8.49	328.4	10.58	10.70	0.83	13.30	11.5	10.5	23.1
	329.0	11.95	11.95	1.08	8.12								
KAOWOOL ZR AS RECEIVED 4 HOURS @ 2600°F 24 HOURS @ 2600°F 168 HOURS @ 2600°F		11.95	12.05	1.25		302.1	11.47	11.25	1.11	8.03	4.3	5.4	14.6
	303.3	11.99	11.89	1.30	6.23	301.7	11.00	11.65	1.05	8.53	7.2	2.9	16.0
	302.0	11.85	12.00	1.25	6.47	297.1	11.13	11.42	1.12	7.94	4.9	5.6	8.9
	298.2	11.70	12.10	1.23	6.52								
CERACHROME AS RECEIVED 4 HOURS @ 2600°F 24 HOURS @ 2600°F 168 HOURS @ 2600°F		11.89	12.42	1.30		331.1	11.40	11.85	1.30	7.19	5.7	3.7	18.8
	331.5	12.09	12.31	1.60	5.30	330.1	11.15	11.30	1.05	9.50	5.9	5.8	19.2
	330.5	11.85	12.00	1.30	6.80	321.5	10.30	11.35	1.09	9.60	13.1	9.6	29.7
	328.7	11.85	12.55	1.55	5.43								
FIBERMAX AS RECEIVED 4 HOURS @ 2600°F 24 HOURS @ 2600°F 168 HOURS @ 2600°F		11.82	11.82	1.27		300.3	11.74	11.73	1.20	6.92	0.8	0.7	0.0
	302.5	11.83	11.81	1.20	6.87	309.8	11.72	11.71	1.26	6.82	1.0	0.7	0.0
	309.9	11.84	11.79	1.26	6.71	309.4	11.53	11.55	1.19	7.73	2.0	1.7	0.0
	312.1	11.76	11.75	1.19	7.22								
SAFFIL AS RECEIVED 4 HOURS @ 2600°F 24 HOURS @ 2600°F 168 HOURS @ 2600°F		11.80	11.80	1.23		315.4	11.45	11.57	1.20	7.55	3.4	2.4	6.3
	317.2	11.85	11.85	1.28	6.72	310.1	11.55	11.59	1.15	7.67	2.3	2.0	0.0
	310.2	11.82	11.83	1.15	7.34	311.1	11.63	11.59	1.20	7.32	1.9	2.2	2.4
	312.6	11.85	11.85	1.23	6.89								

5.4 Thermal Conductivity

The apparent thermal conductivity of the heat treated samples and the as-received samples of each of the five fiber materials was measured at 1000°F mean on a High-Temperature Heat Flow Meter using the test method specified in ASTM C-518. The as-received, 4 h, and 24 h heat treatment samples were tested at thicknesses such that the test densities (within each fiber type) were nearly the same. For example, the Kaowool 2600 samples were tested at 11.6 lb/ft³, while the Kaowool ZR samples were tested at 9.0 lb/ft³. Because the thermal conductivity of refractory fiber blankets changes with changes in density, the adjustment to equal sample density for the thermal conductivity testing allows the evaluation of the effect of heat treating of the fibers themselves rather than the effect of density increases because of shrinkage. The 7 d (168 h) test samples were heat treated after all of the other samples were evaluated for shrinkage and thermal conductivity. Several of the 168 h samples could not be tested at the same density as the other pieces of the same fiber. The after heat treatment thickness of the 168 h pieces was such that the density was significantly higher than the previously tested pieces. For example, the thermal conductivity test on the Kaowool 2600 was performed at a test thickness of 0.72 in., a density of 15.3 lb/ft³. The as-fired thickness was 0.83 in., a density of 13.3 lb/ft³, the minimum density possible for the thermal conductivity test. The initially heat treated samples of Kaowool 2600 were tested at a density of 11.6 lb/ft³. Noting the exceptions of these anomalies, the results of the thermal conductivity testing at "equal" density are shown in Table 5.2 and plotted in Figure 5.2.

The apparent thermal conductivities of all of the heat treated samples were higher than the as-received samples at the same test density. The increase in thermal conductivity ranged from 10% for the Fibermax to 35% for the Kaowool 2600. The thermal conductivity test results were incorporated into the calculation of potential energy savings.

Table 5.2 Apparent Thermal Conductivity at 1000°F Mean

SAMPLE	WIDTH (in.)	FIRE D LENGTH (in.)	THICK (in.)	TEST THICK (in.)	FIRE D WEIGHT (g)	TEST DENSITY lb/ft³	APPARENT THERMAL CONDUCTIVITY BTU-in./h-ft²-°F
KAOWOOL 2600							
AS RECEIVED	12.05	12.12	1.10	0.75	332.2	11.5	0.65
4 h @ 2600°F	10.85	11.11	0.93	0.90	330.0	11.6	0.84
24 h @ 2600°F	10.40	10.98	0.95	0.95	329.4	11.6	0.88
168 h @ 2600°F	10.58	10.70	0.83	0.72	328.4	15.3	0.68
KAOWOOL ZR							
AS RECEIVED	11.95	12.05	1.25	0.90	305.1	9.0	0.71
4 h @ 2600°F	11.47	11.25	1.11	1.00	302.1	8.9	0.83
24 h @ 2600°F	11.00	11.65	1.05	1.00	301.7	9.0	0.83
168 h @ 2600°F	11.13	11.42	1.12	1.00	297.1	8.9	0.77
CERACHROME							
AS RECEIVED	11.89	12.42	1.30	0.90	333.5	9.6	0.71
4 h @ 2600°F	11.40	11.85	1.30	1.00	331.1	9.3	0.78
24 h @ 2600°F	11.15	11.30	1.05	1.05	330.1	9.5	0.83
168 h @ 2600°F	10.30	11.35	1.09	1.09	321.5	9.6	0.82
FIBERMAX							
AS RECEIVED	11.82	11.82	1.27	1.27	309.2	6.6	0.71
4 h @ 2600°F	11.74	11.73	1.20	1.20	300.3	6.9	0.78
24 h @ 2600°F	11.72	11.71	1.26	1.26	309.8	6.8	0.79
168 h @ 2600°F	11.53	11.55	1.19	1.19	309.4	7.4	0.78
SAFFIL							
AS RECEIVED	11.80	11.80	1.23	1.23	316.4	7.0	0.69
4 h @ 2600°F	11.45	11.57	1.20	1.20	315.4	7.6	0.79
24 h @ 2600°F	11.55	11.59	1.15	1.15	310.1	7.7	0.77
168 h @ 2600°F	11.63	11.59	1.20	1.20	311.1	7.3	0.79

Figure 5.2 Thermal Conductivity of Fiber Felts Heat Treated at 2600°F

5.5 Devitrification Studies

All fibers tested exhibited shrinkage and changes in thermal conductivity. These property changes resulted from microstructural changes in the fibers. Devitrification was the microstructural change for the initially vitreous fibers; phase transformations and grain growth were the microstructural changes for the initially crystalline fibers. The experimental studies to characterize the time-temperature microstructural evolution for the fibers tests are summarized in this section.

The 3 x 2 in. samples heat treated at 2600°F for 4, 24, and 168 h (7 d) were used to bracket heating times and temperatures for a detailed devitrification study. Analyses of the phases present before and after heating at 2600°F for 168 h are summarized in Table 5.3. Typical x-ray diffraction patterns are included in Figure 5.3 for Kaowool ZR, showing the vitreous as-received diffuse pattern and the progressive development of the crystalline phases at 2600°F with increasing heat treatment times of 4, 24, and 7 d (168 h). X-ray diffraction patterns for all five fibers are included in Appendix A.2. Typical Scanning Electron Microscopy (SEM) views of the developing crystal

phases in the Kaowool ZR are shown in Figure 5.4. SEM views of all five fibers are included in Appendix A.3.

Table 5.3 Devitrification Products in the Five Selected Fibers Fully Devitrified and As-Received

FIBER	AS-RECEIVED	DEVITRIFIED
Kaowool 2600	Amorphous	Mullite Cristobalite
Kaowool ZR	Amorphous	Mullite Cristobalite t-Zirconia m-Zirconia Zircon
Cerachrome	Amorphous	Mullite Cristobalite
Saffil	delta-Alumina Mullite	Corundum Mullite
Fibermox	Mullite	Mullite

The only difference in the results between the 4 and 24 h heat treatments for all fibers is in the phases present in the Kaowool ZR. Zircon appears only after the 2600°F heat treatment for 168 h. Also, significant shrinkage and changes in thermal conductivity occurred in all samples following the 4 h heat treatment at 2600°F. The time and temperature condition of the fiber for the onset of devitrification became the subject of a more detailed investigation.

Samples of the three vitreous fibers; Kaowool 2600, Kaowool ZR, and Cerachrome, were heat treated at 900°C (1652°F) for 3 h and at 1000°C (1832°F) for 2 h to determine the onset of devitrification. For both the 900 and 1000°C heat treatments each sample weight was ~0.5 g. The samples were cut from the 1 in. thick blankets. The samples were delaminated and stretched into a loose layer of fiber. The samples were placed on a thin layer of the original blanket for the prevention of contamination before being placed inside the furnace at room temperature. The furnace used for the heat-treatment was a Fisher Scientific Isotemp Programmable Furnace, Model 495A. Four furnace parameters can be programmed, namely (a) the heat-up rate, R_1 , (b) the holding time, t , (c) the holding temperature, T , and (d) the cool-down rate, R_2 . The settings for these parameters were:

Parameter	Set 1	Set 2
R_1	30°C/min	30°C/min
t	3 h	2 h
T	900°C	1000°C
R_2	30°C/min	30°C/min

Figure 5.3 X-Ray Diffraction Patterns for Kaowool ZR at Various Heat Treatment Times at 2600°F

KAOWOOL ZR - AS RECEIVED

KAOWOOL ZR - AFTER 4 HOURS @ 2600°F

Figure 5.3 X-Ray Diffraction Patterns for Kaowool ZR at Various Heat Treatment Times at 2600°F (Continued)

KAOWOOL ZR - AFTER 24 HOURS @ 2600°F

KAOWOOL ZR - AFTER 168 HOURS @ 2600°F

Figure 5.4 SEM Views of Kaowool ZR at Various Heat Treatment Times at 2600°F

SEM-18386 KAOWOOL ZR AS-RECEIVED 1000X

SEM-18387 KAWOOL ZR AS RECEIVED 10000X

Figure 5.4 SEM Views of Kaowool ZR at Various Heat Treatment Times at 2600°F (Continued)

SEM-18396 KAOWOOL ZR 4 HRS@2600°F 10000X

SEM-18397 KAOWOOL ZR 4 HRS@2600°F 10000X

Figure 5.4 SEM Views of Kaowool ZR at Various Heat Treatment Times at 2600°F (Continued)

SEM-18406 KAOWOOL ZR 24HRS@2600°F 1000X

SEM-18407 KAOWOOL ZR 24HRS@2600°F 10000X

Figure 5.4 SEM Views of Kaowool ZR at Various Heat Treatment Times at 2600°F (Continued)

SEM-18733 KAOWOOL ZR 168HRS@2600°F 1000X

SEM-18734 KAOWOOL ZR 168HRS@2600°F 10000X

The fiber samples were inserted into the furnace at room temperature. In Set 1, the sample was removed when the furnace temperature reading was dropped to 450°C, while for Set 2 it was removed at 200°C. The Set 1 and the Set 2 samples are referred to as the 900°C and the 1000°C samples, respectively.

All three fibers remained amorphous (vitreous) after heating to 900°C (1652°F) for 3 hours. Devitrification was observed in all three samples after heating to 1000°C (1832°F) for 2 h. Heating times and temperatures for a detailed devitrification study were based on these results. The heating times and temperatures selected for the detailed devitrification study were temperatures of 1800 through 2600°F in increments of 200°F for times of 15, 30, 45, 60 s and 10, 20, and 30 min, as shown in Table 5.4

Table 5.4 Heating Times and Temperatures for Detailed Devitrification Study

Time (°F)	15 s	30 s	45 s	60 s	10 min	20 min	30 min
1800	x	x	x	x	x	x	x
2000	x	x	x	x	x	x	x
2200	x	x	x	x	x	x	x
2400	x	x	x	x	x	x	x
2600	x	x	x	x	x	x	x

The furnace used was an electric indirect resistance furnace, Deltech, Inc., Model DT-31-RS-OS MODE-EMS. The construction is that of a cylindrical body, open at the bottom to accept the hearth. The hearth can be raised and lowered with an electronic control unit that controls the overall heating process. The fiber samples were of two standard sizes for each of the three amorphous fibers, corresponding to the short and the long durations of heat-treatment. Short duration here means the time of heat-treatment is not more than 1 min, i.e., the 15, 30, 45, and the 60 s samples. Long duration refers to the longer treatment times of 10, 20, and 30 min. The sizes for the two sets of treatment are:

Short Duration
2.5 cm x 7.5 cm x 1/4 in.

Long Duration
2.5 cm x 7.5 cm x 1/3 in.

In addition, the short duration samples were loosened before being placed inside the furnace so as to reduce the effect of insulation of the interior portion of the fiber by the outer layer. The time-temperature heat-treatment tests for all fibers were as shown in Table 5.4, except for the short duration Kaowool 2600 samples at 2400°F, which were not obtained because of a malfunctioning

furnace. The samples were inserted into and then removed after the specified time from the hot furnace set at the specified temperature. The short duration samples were inserted into the furnace individually, i.e., one sample of each fiber at a time. The long duration fibers were inserted three samples each time, one each of Kaowool 2600, Kaowool ZR, and Cerachrome. All samples were set on porous zirconia refractory plates, which were heated along with the fiber.

The procedure for heat treating the samples was as follows:

1. Set furnace temperature at desired set point and allow to stabilize
2. Lower the hearth
3. Using long handle tongs, place the zirconia sample holding plate onto the hearth
4. Raise the hearth up into the heated furnace
5. Lower the hearth at the desired time
6. Remove the zirconia plate with the sample to an adjacent stationary hearth
7. Return the empty furnace hearth to the furnace
8. Remove the sample from the zirconia plate for cooling to room temperature.

The time of heat-treatment entered in Table 5.4 is the time of Step 5 above. The samples cool to room temperature in a matter of seconds after being removed (Step 8) from the hot zirconia plate.

The results of the time-temperature devitrification studies are summarized in Tables 5.5 through 5.7. The crystalline phases identified by x-ray diffraction are abbreviated in these tables as:

Mullite = M
 Cristobalite = C
 t-Zirconia = tZ
 m-Zirconia = mZ

Table 5.5 Crystalline Phases in the Devitrification of Kaowool 2600

TEMP (°F)	TIME						
	15 s	30 s	45 s	60 s	10 min	20 min	30 min
2600	M	M	M	M	M	M	M,C
2400	M	M	M	M	M	M	M
2200	M	M	M	M	M	M	M
2000	nil	M	M	M	M	M	M
1800	nil	nil	nil	nil	M	M	M

Table 5.6 Crystalline Phases in the Devitrification of Kaowool ZR

TEMP (°F)	TIME						
	15 s	30 s	45 s	60 s	10 min	20 min	30 min
2600	tZ,M	tZ,M	tZ,M	tZ,M	tZ,M mZ	tZ,M mZ	tZ,M mZ,C
2400	tZ,M	tZ,M	tZ,M	tZ,M	tZ,M	tZ,M	tZ,M
2200	tZ,M	tZ,M	tZ,M	tZ,M	tZ,M	tZ,M	tZ,M
2000	nil	nil	nil	nil	tZ,M	tZ,M	tZ,M
1800	nil	nil	nil	nil	nil	tZ	tZ

Table 5.7 Crystalline Phases in the Devitrification of Cerachrome

TEMP (°F)	TIME						
	15 s	30 s	45 s	60 s	10 min	20 min	30 min
2600	M	M	M	M	M,C	M,C	M,C
2400	M	M	M	M	M	M,C	M,C
2200	M	M	M	M	M	M	M
2000	M	M	M	M	M	M	M
1800	M	M	M	M	M	M	M

The phases present after heat treatment were determined by powder x-ray diffraction. The amount of residual glassy phase present was determined by analysis of the x-ray diffraction patterns. The residual glass present after heat-treatment for the three vitreous fibers, as devitrification proceeds, is summarized in Figures 5.5 through 5.7.

5.6 Significance of the Devitrification Studies

The results of the 4 h heat treatment at 2600°F show that all three vitreous fibers were devitrified at the end of the heating. The results of the detailed devitrification study show that devitrification begins at 1800°F in <15 s for Cerachrome, in <10 min for Kaowool 2600, and in <20 min for Kaowool ZR. For these three vitreous refractory insulating fibers, the microstructural changes that result in the loss of insulating properties occur the first time the fibers are brought to operating temperatures above 1800°F.

Figure 5.5 Amorphous Residual During Devitrification of Kaowool 2600

Figure 5.6 Amorphous Residual During Devitrification of Kaowool ZR

Figure 5.7 Amorphous Residual During Devitrification of Cerachrome

6. ENERGY SAVINGS ANALYSIS

6.1 Selection of Furnaces for Modeling

There are two types of high temperature (500 to 1700°C) heating processes in the manufacturing industries. These are the batch and continuous duty heating processes. Batch furnaces have two basic geometries, cylindrical and rectangular box. Whereas the continuous duty furnaces occur in the rotary hearth, or toroidal, and the rectangular tunnel geometries.

Because the capabilities of both computer programs used in this study were limited to modeling two-dimensional geometries, the only batch furnace numerically modeled was the cylindrical or axisymmetric furnace, with the axis of symmetry parallel to the gravitational vector. Bell or pit furnaces are frequently designed with a cylindrical geometry in this orientation (Koch, 1987). A schematic of this type of furnace is shown in Figure 6.1.

In addition to the cylindrical furnace, three continuous duty furnaces such as the walking beam, rotary hearth, and tunnel kiln were modeled and schematics are provided for these furnaces in Figures 6.2, 6.3, and 6.4. The physical dimensions of the rotary hearth and tunnel kiln were those of furnaces currently operating at local brick and steel manufacturers, respectively. Tours of both facilities were beneficial in the pursuit of acquiring dimensional and working energy consumption data on these furnaces (Arner, 1989, Stumpff, 1989 and Moore and Walker, 1989). The dimensions of the walking beam were obtained from the literature (Braun, 1982).

6.2 Cylindrical and Box Batch Furnaces

The cylindrical batch furnace modeled in this study was similar to a coil steel annealing furnace (Jaluria, 1984). The interior boundary conditions for the modeled furnaces differed slightly from each other. The cylindrical batch furnace and the continuous duty walking beam furnaces were the first to be modeled and rather complicated procedures were utilized to approximate the radiative heat transfer from the flame and hot gases to the inner wall (Blok, 1988 and Cai, 1990). In addition, the convective heat transfer coefficient for the inner cylindrical furnace wall was determined from standard external flow heat transfer correlations (Incropera and DeWitt, 1990). The gas velocity was assumed to be 10 m/s (Jaluria, 1984). As shown in Figure 6.1, the walls were modeled as composite layers of refractory fiber insulation with successively lower bulk densities from the inside and moving outward. The properties of Cerachrome were used in this model.

Because three-dimensional computer programs were not available for this study, an alternate analysis was performed comparing the results of the axisymmetric batch furnace and a rectangular box furnace. Conduction shape factors (Incropera and DeWitt, 1990) were used to approximate the steady state heat loss through a box furnace. The basic assumption made in utilizing this technique is that the inside and outside furnace wall temperatures are known and uniform. The horizontal box interior dimensions were assumed to be square and the area was assumed to be equal to the area of the axisymmetric case modeled by computer. This is believed to be a reasonable assumption because both furnaces could be used to heat the same size product. A comparison of these batch furnace geometries is provided in Subsection 6.7.

Figure 6.1 Cylindrical Furnace Model

Figure 6.2 Typical Walking Beam Furnace

Figure 6.3 Typical Rotary Hearth Furnace

Figure 6.4 Typical Tunnel Kiln Section

6.3 Walking Beam, Rotary Hearth, and Tunnel Kiln Continuous Duty Furnaces

The continuous duty furnaces were divided into different zones for modeling purposes. This approach is similar to the methods used to control furnace operation. In the industrial furnaces that were observed in operation (Moore and Walker, 1989, Stumpff, 1989 and Arner, 1989), each zone had a bank of burners that were controlled by temperature set points for that particular zone. Fuel was added to the burners in each zone until the set point temperature was reached. As heat losses occur in the zone, the zone temperature drops, resulting in a control signal for the burners to cycle ON, until a tolerance on the temperature set point was exceeded, then back off again, thereby maintaining a nearly constant zone temperature.

The walking beam furnace was modeled using the thermal properties of fibers whose working temperatures coincide with appropriate industrial zonal temperatures. Table 6.1 provides the operating and fiber working temperature used in each zone of a typical walking beam furnace.

Table 6.1 Operating Conditions for the Walking Beam Furnace in Three Zones

ZONE	OPERATING TEMPERATURE		FIBER TYPE
	°F	°C	
Soak	2350	1288	SAFFIL
Heat	1850	1010	FIBERMAX
Preheat	1400	760	KAOWOOL 2600

The inner wall boundary conditions for the walking beam furnace were flame and gas radiation and forced convection. The flame and gas temperatures were taken to be the temperature set point for that particular zone. Each zone was also assumed to have a large blower providing well mixed preheated air over the product. Assumed blower capacities were similar to those used in industry (Moore and Walker 1989). A zero-order model was used to approximate the convective velocity from the blower volumetric flow rates. The convective coefficients were then determined from standard forced convective heat transfer correlations.

Inner wall temperatures for the rotary hearth and tunnel kiln were assumed to be constant and uniform over the entire zone. As in the walking beam furnace, actual temperature set points for local industrial furnaces were used (Moore and Walker, 1989 and Stumpff, 1989). The boundary conditions for the cylindrical and walking beam furnaces are described by Cai, (1990). Four zones were modeled in the rotary hearth and three zones were modeled in the tunnel kiln, as shown in Table 6.2. All of the furnaces were modeled using convective and radiative boundary conditions at the outer wall surface.

Table 6.2. Temperature Set Point for Industrial Furnace Zones

FURNACE TYPE	Temperature Set Points (°C)			
	Zone 1	Zone 2	Zone 3	Zone 4
Rotary Hearth	1038	1149	1204	1232
Tunnel Kiln	982	1071	1177	

6.4 Selection of the Computer Programs

Two computer codes previously developed by the Department of Energy were used to model heat losses through the walls of industrial furnaces. The code names are Determination of Temperature, DOT (INTERA, 1982) and TOPAZ2D (Shapiro, 1986). The DOT code was chosen because it could be run on an International Business Machines (IBM) compatible personal computer, which allows the use of the DOT program in a typical industrial setting. It was desirable to develop the

capability of taking the program (loaded in a lap top PC) into an industrial environment to quickly analyze a furnace wall and storage heat losses to prove the potential energy savings when an improved refractory fiber is used over existing fiber or refractory brick.

The running time for the DOT program is acceptable on the PC, primarily because the nonlinear boundary conditions associated with the radiation component of heat transfer are linearized with a simplified noniterative technique. However, this simplification, although resulting in higher program efficiencies, can result in substantial inaccuracies in the heat loss calculation. Therefore, the TOPAZ2D code was chosen as a secondary model because of its added sophistication to verify the accuracy of the DOT code results. However, it must be run on a much faster main frame or mini computer. The DOT code provided the most reliable results when the radiation boundary condition was avoided at the inside or hot furnace surfaces. Computer runs of the DOT code that included convective and radiative boundary conditions at the outer surface yielded acceptable agreement with identical conditions run in the TOPAZ2D code. The only exception to this is in the outer boundary element immediately adjacent to the axis of symmetry of the cylindrical furnace model. However, this aberration did not significantly affect the energy calculation results. Although there are these concerns about inaccuracies of the DOT code, heeding the warnings described above, the results from both computer codes compare well with several analytical solutions (Cai, 1990) and with each other when the inside surface boundary condition is a known and uniform temperature. Figures 6.5 and 6.6 provide a comparison of runs with identical conditions performed on both the DOT and TOPAZ2D codes.

Both programs utilize the finite element technique and can be used to solve two-dimensional, axisymmetric, or cartesian transient heat conduction problems with radiation and convection or known temperature boundary conditions. Also, both programs are capable of modeling thermal systems that involve thermophysical property variations with temperature. The rather weak nonlinearities associated with temperature dependent properties do not compromise the accuracy of either program. However, the strong nonlinearities introduced by the radiation boundary conditions can have a significant effect on the results of the DOT code (particularly when the temperatures are high, as for common furnace operating temperatures) and near lines of symmetry such as near the centerline of the axisymmetric geometries. In general, both programs have been used extensively in this study and in other science and engineering projects (INTERA, 1982 and Shapiro, 1986). Therefore, the level of confidence in the codes (with knowledge of the above mentioned limitations) remains high.

Figure 6.5 Comparison of DOT and TOPAZ Codes, Cold-Side

Figure 6.6 Comparison of DOT and TOPAZ Codes, Wall Mid-Plane

6.5 Modification of the Computer Codes

The DOT and TOPAZ2D codes were written to calculate the temperature distribution of the thermal system of interest. However, the DOT code did not have the capabilities of calculating the steady state wall heat losses or the transient wall energy storage. Modifications of the code were made to account for these heat losses and storage factors.

Steady state wall losses were determined by summing the radiation and convection heat losses for each boundary element at the outer wall surface. These outer wall losses were determined with knowledge of the steady state outer surface temperature and the convective and radiative heat transfer coefficients. Convective coefficients were determined with standard empirical free convection heat transfer correlations. The radiative heat transfer coefficient is a function of the outer wall surface emissivity and the temperatures of the outer wall surface and surroundings (Incropera and DeWitt, 1990). With the exception of the inner outside wall of the toroidal rotary hearth furnace, the geometrical configuration factor from the outer furnace wall to the surroundings was taken to be 1. Differential configuration factors were used for the radiation boundary conditions on the inner outside wall of the rotary hearth because that wall could see itself, thereby resulting in a reduction in radiative losses caused by the relatively high inner toroid outer wall temperatures.

The energy storage calculation was performed for each element in the domain. The difference between the element final and initial temperatures was multiplied by the bulk density and the temperature dependent specific heat of the refractory fiber wall. After steady state was reached, the energy storage for each element was summed to yield the total energy required to heat the furnace wall from standard ambient temperature to the furnace operating temperature.

6.6 Fiber Properties Used in the Modeling

As indicated in Section 5., the thermal conductivity and shrinkage of the refractory fibers chosen for this study were measured both in the as-received state and after heat treatment. The as-received fiber thermal physical properties are designated as "enhanced" and the properties of the fibers after heat treatment are designated as existing. The properties of an enhanced fiber therefore represent the desired thermal physical properties of an improved fiber that remains amorphous after heat treatment. The energy losses for each furnace using both enhanced and existing fibers are compared in the next section. The difference in the calculated energy losses represents the potential energy savings when an improved fiber is used over an existing, commercially available fiber.

6.7 Modeling Results

The results from the modeling activities are tabulated in Table 2.2. Table 2.2 provides a comparison of the calculated steady state heat losses for the furnaces chosen for analysis in this study. Each furnace was modeled with various fibers in place. The cylindrical furnace was modeled using the properties for the three bulk densities of Cerachrome. The Walking beam insulating materials are listed in Table 6.1. Thermal properties of Kaowool 2600 were used to model the inner lining of the rotary hearth furnace and tunnel kiln. The comparison shows that there is the potential for substantial energy savings when an improved fiber is used over those that are currently commercially available. The steady-state results indicate that, for the furnaces modeled, 11 to 19% of the heat transferred through the wall can be saved when using an enhanced fiber over an existing fiber. These percentages will be used in Section 7 to determine the annual potential energy savings for the primary metal reheat, ferrous metal heat treating, and ceramic heating processes in the United States.

Because it was impossible to model a rectangular (box) batch furnace numerically in this study, a simplified comparison between a box and cylindrical furnace was employed. The steady state wall heat losses for the cylindrical furnace were determined with known and uniform temperature boundary conditions inside and out of $T_{in} = 1000^{\circ}\text{C}$ and $T_{out} = 100^{\circ}\text{C}$. The physical dimensions were the same as shown in Figure 6.1. For this configuration, the steady state wall heat losses were 14.8 kW. A technique involving conduction shape factors (Incropera and DeWitt, 1990) was used to determine the steady state losses from a rectangular furnace with the same horizontal cross-sectional area, height, and insulation thickness. The wall loss for this box furnace was 14.1 kW. With the rough approximations made, it is reasonable to assume that the percent of wall heat losses from the cylindrical furnaces are similar to those of rectangular furnaces with the same internal volume.

The storage losses determined from the transient analysis of the cylindrical furnace, insulated with enhanced and existing fibers, are compared in Table 6.3. Note that the difference in the storage losses when the enhanced and existing fibers are used is small, averaging ~4%. Nonetheless, it was interesting to find that there was a difference in heat storage between the furnaces using the enhanced and existing fiber. Because the mass of the enhanced and existing fibers was the same, the small difference in heat storage is caused by the differences in the calculated temperature distributions and the corresponding effect on the temperature dependent specific heat for the two cases. According to Koch, (1987) nearly 80% of the furnaces used in the ferrous metal heat treating industries, ~1/3 of the energy consumption sector under consideration in this study, are batch furnaces. Therefore, a 4% reduction in each cycle of the batch furnaces in these industries

could yield a significant energy savings. The uncertainties that remain regarding the number of batch furnace cycles per year and lower temperature limit between cycles will require further study.

Table 6.3 Energy Losses Through the Enhanced and Existing Fiber Wall in the Cylindrical Furnace

MATERIAL	CODE	Wall Heat Losses (10 ³ Btu/h)	Heat Storage (10 ³ Btu/h)	Total energy (10 ³ Btu/h)
Enhanced Fiber	DOT	137.75	66.21	204.00
Existing Fiber	DOT	153.82	72.38	226.24
Energy Saving Rate (%)		10.4	8.5	
Enhanced Fiber	TOPAZ	130.53	55.83	186.42
Existing Fiber	TOPAZ	145.43	56.14	201.55
Energy Saving Rate (%)		10.3	0.5	

6.8 Energy Savings Calculation

Recall that these are the energy consumption estimates (McDermott and Chapman, 1988) for specific processes in the primary metals reheat, ferrous metal heat treating, and ceramic heating industries (See Table 2.1). These were the process areas that the authors felt were the most appropriate for refractory fiber usage. The energy consumption is divided into two categories, electrically heated furnaces and gas or other fossil fuel. The electrical energy consumption column of Table 2.1 was summed and divided by 0.34, which represents the efficiency of converting another conventional fuel into electricity. This figure was added to the sum of the furnaces burning fossil fuels, resulting in 0.7035 quad of energy consumed in the industries chosen for this detailed analysis.

A literature survey was performed in an attempt to estimate the fraction of energy losses associated with the furnace wall. Wall heat losses can account for 5 to 38% of the total energy input. Table 6.4 lists a number of batch and continuous furnaces previously analyzed (Budacki, 1983, Casana and Stabile, 1983, Hollander and IJmuiden, 1983, Molloy, 1985, Viskanta and Menguc, 1987, and Vance, 1985). An average wall heat loss of 10 to 20% was assumed to be a conservative estimate for the furnaces considered in this study.

Table 6.4 Reported Wall Heat Losses for Typical Industrial Furnaces

FURNACE	WALL LOSSES (%)	REFERENCES (author)
Soaking Pit	10	Hollander
Pusher Slab Reheating	13 to 20	Vance
Radiant Tube Heat Treat	22 to 38	Industrial Heating
Flashheat	9	Molloy
Roller Hearth Reheating	5 to 10	Budacki
Continuous Walking Beam Hardening	9 to 11	Casana
Continuous Walking Beam Tempering	16	Casana
Preheat	14	Molloy
Typical Industrial	14	Viskanta

The modeling results, Subsection 6.7, indicate that 11 to 19% of the wall losses could be saved when using an enhanced over an existing refractory fiber. Combining the percent wall losses (Table 6.4) of the total furnace input energy and the percent savings when an enhanced fiber is used over existing fiber, yields 1.1 to 3.8% energy savings when an enhanced refractory fiber is used over a commercially available fiber. The resultant potential annual savings ranges from 0.0077 to 0.0267 quad.

Although only the Metals and Ceramics industries were specifically targeted for application of an improved refractory fiber, the Chemicals and Allied Products and Petroleum and Coal Products industries consume many times more energy. According to a report by the Energy Information Administration (1988), Chemicals and Allied Products consumed 3.567 quad annually and Petroleum and Coal Products consumed 5.123 quad annually. Possible applications, at temperatures exceeding 1500°C, of enhanced refractory fiber in the Chemical and Allied Products industries include:

1. Heater and reformer linings
2. Pigtail insulation
3. Reformer header insulation
4. Lining of hot gas ducts
5. Weld insulation.

In the Petroleum and Coal Products industries, Fineproofing at 1300°C (one process) was identified as having potential for use of refractory fiber. However, a less than exhaustive search was performed in these industries, primarily because it was felt unnecessary to meet the required criteria of 0.01 quad annual energy savings. In addition, there are numerous processes, in the glass and aluminum industries, that are also potentially appropriate for use of refractory fiber

materials. Therefore, a much more detailed analysis will be required in these industries to identify the specific processes where refractory fiber usage is feasible.

A rough estimate of the energy savings potential in the chemical and petroleum industries can be made if it is assumed that 50% of the energy consumed in these industries is associated with high temperature, nonreducing processes. As before, if 10% of the energy input to these processes is lost through the furnace walls and 10% of this energy can be saved through the use of an improved refractory fiber, then an additional 0.044 quad of energy could be saved annually in the chemical and petroleum industries.

During visits to local refractory and steel manufacturers, it was found that workers would use fiber to fill between cracks that develop between refractory brick and around furnace door jambs. Modeling the heat loss savings for this application was not performed. However, improved fiber properties could also result in substantial energy savings for this type of application.

7. TECHNOLOGY SUMMARY

The objectives of this first research phase have been to assess the current technology and use patterns of existing refractory fibers, to establish a data base on currently used refractory fibers, and to develop an estimate of the potentially attainable energy savings as a result of developing enhanced insulating property and service lifetime fibers.

The current use patterns of refractory fibers span a wide range of industries and high temperature furnaces within those industries. The majority of high temperature fiber applications are in furnaces operating between 2000 and 2600°F. The fibers used in furnaces operating within this range provide attractive thermal resistance and low thermal storage at reasonable cost. Higher temperature applications require significantly more expensive materials. The applications and analyses of the observed savings through the use of existing refractory fibers has been documented in the literature as included in the technology data base included in this report.

A series of heat treatment studies performed for this phase of the program has shown that the refractory fibers as initially manufactured have attractive thermal conductivities for high temperature applications but the fibers go through rapid devitrification and subsequent crystal growth upon high temperature exposure. Exposure of the as-manufactured fibers to furnace temperatures well below the service temperatures of the fibers causes significant thermal conductivity and microstructural changes. This results in higher heat losses through the furnace walls and shortened service lifetime because of increased brittleness of the fibers.

Development of improved fibers (maintaining the favorable characteristics of the existing as-manufactured fibers) could save between 1 and 4% of the energy consumed in high temperature furnaces using refractory fibers. This savings is on the order of 0.01 to 0.03 quad Btu/y. These savings have been calculated based on models comparing furnaces insulated with existing fibers that degrade and furnaces insulated with the to be developed fiber(s) of this program.

The devitrification studies performed for this phase indicate that the rate of crystalline phase development is quite rapid but possibly can be limited or suppressed sufficiently so that the fibers can retain the favorable characteristics of the vitreous as-manufactured fibers. Combining the proper refractory oxide phase compositions with properly controlled fiberization processes could result in new improved high temperature fibers.

8. REFERENCES

- Arner, Wayne, Personal Communication, Coors Ceramics Company, Golden, CO, August 1989.
- Blokh, A.G., Heat Transfer in Steam Boiler Furnaces, Hemisphere Publishing Corp., 1988.
- Budacki, J.E., "Roller Hearth Furnace with High Velocity Jet Burners Saves Fuel in Reheating Plate Uniformly", Industrial Heating, no. 12, December 1983, pp. 30-32.
- Cai, Yifang, "Numerical Modeling of Heat Transfer in a Furnace Wall at High Temperature with Convection and Radiation Boundary Conditions", M.S. Thesis in Applied Mechanics, T-3979, Colorado School of Mines, December 1990.
- Casana, A. and Stabile, V., "Continuous Walking Beam Furnace Facility -- Design Aspects and Operating Data for Heat Treating Cylinders", Industrial Heating, no. 10, October 1983, pp. 42-43.
- Christiansen, Russell, Personal Communication, Geneva Steel, Salt Lake City, UT, 1989.
- Courier, B., Gleitzer, G., Poirson, G., and Sevilaud, L., "Etude de la Recristallisation de Fibres Refractaires", Rev. Int. hautes Temper. Refract. Fr., 19, pp. 9-17, 1982.
- Energy Information Administration (EIA), "Manufacturing Energy Consumption Survey: Consumption of Energy, 1985", Department of Energy Report, DOE/EIA-0512(85), November 1988.
- Ganz, R. and Kronert, W., "Crystallisation Behavior of High Temperature Ceramic Fibers of the Al_2O_3 - SiO_2 System", Interceram, NR.2, 1982 pp. 136-144.
- Gaodu, A.N., Pitak, N.V., Vol'fson, R.E., and Drizheruk, M.E., "Crystallization in Heated Aluminosilicate Fibers", Izv. Akad Nauk SSSR. Neorg. Mat., 13, (12), 1977 pp. 2265-2268.
- Hollander, F., IJmuiden, H., "Reheating Processes and Modifications to Rolling Mill Operations for Energy Savings", Iron and Steel Engineer, June 1983, pp. 55-62.
- Incropera, F.P. and DeWitt, D.P., Fundamentals of Heat and Mass Transfer, Wiley, 3rd Edition, 1990.
- INTERA, "DOT - A Nonlinear Heat Transfer Code for Analysis of Two-dimensional Planar and Axisymmetric Representations of Structures", INTERA Environmental Consultants Inc., Report OMWI/E512-02900/CD-16, 1982.
- Jacobs, Stan, Personal Communication, ALCOA Aluminum, Pittsburg, PA, 1990.
- Kerfer, J.R., "Ceramic Fiber Insulation Furnace Research Program", GRI - 86/0202, 1986.
- Koch, G.S., McDermott, H. and Klareich, F.H., "Competitive Position of Natural Gas: Ferrous Metal Heat Treating and Atmosphere Generation Applications", Report to the Gas Research Institute, GRI-87/0001, by Hagler, Bailly & Co., October 1987.
- Lippert, Jim, Personal Communication, Kaiser Aluminum, Pleasanton, CA, 1990.
- Lo, P., "Devitrification and Recrystallization Processes in Ceramic Refractory Fibers" M.S. Thesis, CSM Thesis Number T-4004, Colorado School of Mines, Golden, CO (1991).

McDermott, H. and Chapman, M.A., "U.S. Industrial Process Heating Energy Consumption - 1985", Report to the Gas Research Institute, GRI-88/0051, by Hagler, Bailly & Co., February 1988.

Molloy, T.J., "Developments in the Use of Ceramic Fiber to Achieve Energy Reduction in Steel Re-heating Furnace", SEAIISI Quarterly, no. 7, July 1985, pp. 14-26.

Moore, Winston and Walker, Walter, Personal Communication, CF&I Steel Company, Pueblo, CO, 1989.

Riley, Burt and Ellers, Tom, Personal Communication, CF&I Steel Company, Pueblo, CO, 1990

Schulle, W., Ruppelt, R., and Toppler, B., "Beeinflussung des thermischen Verhaltens feuerfester aluminiumsilikatischer Fasern durch Cr_2O_3 -Zugabe", Silikattechnik, 37, Heft 11, 1986 pp. 377-379.

Shapiro, A.B., "TOPAZ2D - A Two-dimensional Finite Element Code for Heat Transfer Analysis, Electrostatic and Magnetostatic Problems", University of California, Lawrence Livermore National Laboratory, Report UCID-20824.

Sterahan, Dennis, Personal Communication, Reynolds Aluminum, VA, 1990.

Stumpff, Milton, Personal Communication, Robinson Brick Company, Denver, CO, 1989.

Thring, M.W., The Science of Flames and Furnaces, New York: John Wiley and Sons Inc., 1952.

Vance, M.W., "Development of a Non-welded Skid-pipe Insulation for Steel Plant Reheat Furnaces", Industrial Heating, April 1985, pp. 22-26.

Viskanta, R. and Menguc, M.P., "Radiation Heat Transfer in Combustion Systems," Progress in Energy Combustion Science, 13, 1987, pp. 97-160.

Wargo, Thomas, Personal Communication, Salem Furnace Company, Pittsburg, PA, 1990.

APPENDIX A.1
REFRACTORY INSULATING FIBER DATA BASE

APPENDIX A.1 Refractory Insulating Fiber Data Base

CATEGORY CODES	ES-C	Energy Savings: Cases
	ES-F	Energy Savings: Fiber
	ES-I	Energy Savings: Insulation
	ES-T	Energy Savings: Trade
	ES	Energy Savings: Other
	F-C	Furnace: Construction
	F-O	Furnace: Operation
	F-S	Furnace: Simulation
	F	Furnace: Other
	RF-P	Refractory Fiber: Products
	RF-E	Refractory Fiber: Experiment
	RF	Refractory Fiber: Other
	AOB	Any Other Business

ID	1
AUTHOR	Molloy T J
TITLE	Developments in the use of Ceramic Fibre to Achieve Energy Reduction in Steel Re-heating Furnaces
CITATION	SEAISI Quarterly v 14 n 3 Jul 1985 p 14-26
CATEGORY	ES-C
REMARK	This paper is a classic reference for the Manville-CSM Project.
ID	2
AUTHOR	Anon.
TITLE	Efficiency of Forge Furnace in Canada Increased with Refractory Fiber and Recuperation
CITATION	Industrial Heating v 52 n 4 Apr 1985 p 55
CATEGORY	ES-C
REMARK	Fiber + Recuperation = 53% fuel savings = 15% from fiber and 38 % from recuperator
ID	3
AUTHOR	Tye R P
TITLE	Improved Energy Recovery: Upgrading Thermal Insulation Performance of Industrial Processes
CITATION	Chemical Engineering Progress v 81 n 2 Feb 1985 p 30-34
CATEGORY	ES-F
REMARK	
ID	4
AUTHOR	Kyne W P
TITLE	Refractory Fiber as an Insulation in the Forge Industry
CITATION	Industrial Heating v 51 n 7 Jul 1984 p 31-33
CATEGORY	ES-C
REMARK	

ID	5
AUTHOR	Musick G, Schuler L
TITLE	Ceramic Fiber Refractory Improves Efficiency at Druon
CITATION	Die Casting Engineer v 27 n 3 May-Jun 1983 p 14
CATEGORY	ES-C
REMARK	
ID	6
AUTHOR	Anon.
TITLE	Refractory Fiber Lining System Greatly Increases Efficiency and Productivity of Billet Reheat Furnace
CITATION	Industrial Heating v 50 n 9 Sep 1983 p 46
CATEGORY	ES-C
REMARK	
ID	7
AUTHOR	Venable C R, Rahman S F
TITLE	Current Refractory Trends in Refining/Petrochemical Operations
CITATION	American Ceramic Society Bulletin v62 n7 Jul 1983 p 775-778
CATEGORY	ES-F
REMARK	
ID	8
AUTHOR	Cenedella A J
TITLE	Refractory Fiber in Heat Treating Operations
CITATION	Metal Progress v 122 n 5 Oct 1982 p 41-45
CATEGORY	ES-F
REMARK	
ID	9
AUTHOR	Snyder J E, Petit M R
TITLE	Refractory Fiber Lining Design for High Temperature Metal-Heating Furnaces
CITATION	American Ceramic Society Bulletin v 61 n 7 Jul 1982 p 715-71
CATEGORY	ES-F
REMARK	
ID	10
AUTHOR	Miiller, William C.; Scripps, Thomas A.
TITLE	Relating Apparent Thermal Conductivity to Physical Properties of Refractory Fiber
CITATION	American Ceramic Society Bulletin v 61 n 7 Jul 1982 p 711-71
CATEGORY	RF-P
REMARK	
ID	11
AUTHOR	Anon.
TITLE	New Method Rapidly and Accurately Measures 'K' Values of Refractory Fiber Insulation
CITATION	Industrial Heating v 49 n 4 Apr 1982 p 22-23
CATEGORY	RF-P
REMARK	

ID	12
AUTHOR	Braun R C, Parker W H
TITLE	Refractory Fiber Modules Saves Fuel in a Walking Beam Billet Heating Furnace
CITATION	Industrial Heating v 49 n 4 Apr 1982 p 12-14
CATEGORY	ES-C
REMARK	
ID	13
AUTHOR	Anon.
TITLE	Heat Treating Furnaces Lined with Refractory Fiber to Increase Fuel and Operating Efficiencies
CITATION	Industrial Heating v 48 n 4 Apr 1981 p 24-25
CATEGORY	ES-C
REMARK	
ID	14
AUTHOR	Clark R S
TITLE	Selecting Insulating Refractory -- economic considerations and types
CITATION	Plant Engineering(Barrington, Illinois) v32 n3 Jan 5 1978 p
CATEGORY	ES-F
REMARK	
ID	15
AUTHOR	Clark R S
TITLE	Selecting Insulating Refractory -- typical applications
CITATION	Plant Engineering(Barrington, Illinois) v32 n3 Feb 2 1978 p
CATEGORY	ES-F
REMARK	
ID	16
AUTHOR	Langman C A
TITLE	Furnace builders, users warm to alumina fibres
CITATION	Chartered Mechanical Engineer v 24 n 8 Sep 1977 p 92-93
CATEGORY	ES-F
REMARK	Introduces Saffil by ICI.
ID	17
AUTHOR	Anon.
TITLE	Furnace lining system cuts installation time
CITATION	Chemical Engineering (NY) 84 n 13 Jun 20 1977 p 83-84
CATEGORY	RF-P
REMARK	Discusses Z-Blok (ease of) installation.
ID	18
AUTHOR	Fryatt J
TITLE	Low thermal mass furnace linings
CITATION	Energy World v 24 Feb 1976 p 7-12
CATEGORY	ES-C
REMARK	Useful

ID	19
AUTHOR	Neal J E
TITLE	Role of Refractory Fiber in Insulation of Reheat Furnaces
CITATION	Industrial Heating v 37 n 1 Jan 1970 p 122, 124-126, 128, 13
CATEGORY	ES-F
REMARK	
ID	20
AUTHOR	Stanford K
TITLE	ENERGY SAVING IN THE METAL INDUSTRIES
CITATION	ENERGY SAVING IN THE METAL INDUSTRIES
CATEGORY	ES
REMARK	CSM HD9506G72E5. A STEEL TIMES, METALLURGIA and FOUNDRY trade journal supplement. Very useful.
ID	21
AUTHOR	Eltzroth, John M.
TITLE	Fuel Savings with Ceramic Fiber Covers for Computerized Soaking Pits
CITATION	Ind. Heat. v 56 n 12 Dec 1989 p 37
CATEGORY	ES-C
REMARK	Soaking pit cover. Armco Steel Co.
ID	22
AUTHOR	Otskey, Vince
TITLE	Furnace Curtains Made from Silica-Based Refractory Fabric Effective in Saving Energy
CITATION	Ind. Heat. v 56 n 6 Jun 1989 p36
CATEGORY	ES-C
REMARK	Curtains. Slab reheat & heat treatment furnace.
ID	23
AUTHOR	Deren G W
TITLE	Reheat Furnace for Superalloys and Titanium Alloys Redesigned with Ceramic Fiber Lining for More Efficient Processing
CITATION	Ind. Heat. v 56 n 4 April 1989 p 43
CATEGORY	ES-C
REMARK	Reheat furnace for forging. Teledyne Allvac.
ID	24
AUTHOR	Deren G
TITLE	Efficient Forging of Alloy Steels Using Improved Furnaces at LTV Steel
CITATION	Ind. Heat. v 55 n 6 Jun 1988 p 23
CATEGORY	ES-C
REMARK	Fiber module replaces firebrick. Reheat furnace for forging. LTV Steel
ID	25
AUTHOR	Clark R
TITLE	Controlled Combustion of Ceramic Fiber Lined Furnaces Highly Efficient in Annealing Alloy Rolls
CITATION	Ind. Heat. v 55 n 4 April 1988 p 34
CATEGORY	ES-C
REMARK	Heat treatment furnace for annealing alloy rolls. Johnstown Corp. Shows temperature profile for a 7-day heat treating cycle.

ID	26
AUTHOR	Anon.
TITLE	Ceramic Fiber Lined Incineration System of Regenerative Type Meets Clean Air Standards in Cogenerative Use
CITATION	Ind. Heat. v 55 n 4 April 1988 p 28
CATEGORY	ES
REMARK	
ID	27
AUTHOR	Anon.
TITLE	Protective Coating and Ceramic Fiber System Effective in Refinery Furnace Operation
CITATION	Ind Heat. v 54 n 12 Dec 1987 p 35
CATEGORY	ES
REMARK	Methane reformer furnace. Avon refinery, Tosco Corp.
ID	28
AUTHOR	DeSousa T
TITLE	Forge Furnace Relined with Vacuum-Formed Ceramic Fiber Logs
CITATION	Ind. Heat. v 54 n 11 Nov 1987 p 28
CATEGORY	ES-C
REMARK	Slot-forge furnace. Midland Forge Division, Columbus McKinnon Corp.
ID	29
AUTHOR	Barnes, Donald C
TITLE	Energy Conservation Reflected in History of Modernization at Monroe Forgings
CITATION	Ind. Heat. v 54 n 11 Nov 1987 p 24
CATEGORY	ES-C
REMARK	Slot-forge furnace. Monroe Forgings, AMCA International.
ID	30
AUTHOR	Anon.
TITLE	New High Temperature Ceramic Fiber Blanket Providing High Strength and Low Shrinkage in Kiln Operation
CITATION	Ind. Heat. v 53 n 11 Nov 1986 p 52
CATEGORY	ESC
REMARK	Kiln car insulations. Tunnel kiln. Artesian Industries.
ID	31
AUTHOR	Barrows, Jerry
TITLE	New Sprayable Ceramic Fiber with Special Binder Provides Economical System for Insulating Furnaces
CITATION	Ind. Heat. v 53 n 4 April 1986 p 20
CATEGORY	ES-C
REMARK	Sprayable ceramic fiber from Carborundum. Carbottom heat treating furnace.
ID	32
AUTHOR	Hounsel, Mack A.
TITLE	Design and Use of Composite Ceramic Fiber Furnace Curtain at Cameron Iron Works
CITATION	Ind. Heat. v 52 n 8 Aug 1985 p 41
CATEGORY	ES-C
REMARK	Nextel 312 ceramic fiber of 3M.

ID	33
AUTHOR	Anon.
TITLE	Refractory Fiber Modules Used to Line Fire Test Furnaces at Research Institute
CITATION	Ind. Heat. v 52 n 7 Jul 1985 p 36
CATEGORY	ES-C
REMARK	Cerablanket Z-Blok
ID	34
AUTHOR	Anon.
TITLE	Over 38% Fuel Savings Documented for Continuous Heat Treating Furnace Retrofit
CITATION	Ind. Heat. v 52 n 3 March 1985 p 24
CATEGORY	ES-C
REMARK	
ID	35
AUTHOR	Kyne, W. P.
TITLE	Spray-On Fiber Linings for Continuous Stainless Steel Strip Furnaces Increase Their Efficiency
CITATION	Ind. Heat. v 51 n 11 Nov 1984 p 42
CATEGORY	ES-C
REMARK	
ID	36
AUTHOR	Anon.
TITLE	Insulation of High Temperature Forge Furnaces Using Fiber over Fiber Technique
CITATION	Ind. Heat. v 51 n 10 Oct 1984 p 46
CATEGORY	ES-C
REMARK	
ID	37
AUTHOR	Anon.
TITLE	Porcelain Enameling Furnaces Retrofitted with Ceramic Fiber to Increase Fuel Savings and Production
CITATION	Ind. Heat. v 51 n 7 Jul 1984 p 34
CATEGORY	ES-C
REMARK	Counterflow Furnaces, U-Type Furnace, Muffle Furnace, Batch Furnace.
ID	38
AUTHOR	Kyne, W. P.
TITLE	Refractory Fiber as an Insulation in the Forging Industry
CITATION	Ind. Heat. v 51 n 7 Jul 1984 p 31
CATEGORY	ES-C
REMARK	Modern Drop Forge Co.
ID	39
AUTHOR	Anon.
TITLE	Veneering with Fiber Modules Saves Fuel in Timken's Reheat Furnace
CITATION	Ind. Heat. v 51 n 4 April 1984 p 38
CATEGORY	ES-C
REMARK	Rotary Hearth Furnace. Lining Over Refractories(L.O.R.).

ID	40
AUTHOR	Ploehn, G.
TITLE	Designed Forge Furnace Modification at Stanley Works Decreases Fuel Cost 72%
CITATION	Ind. Heat. v 51 n 4 April 1984 p 34
CATEGORY	ES-C
REMARK	(1)Z-Blok replaces brick (2)air/fuel ratio (3)automatic temperature control (4)recuperator
ID	41
AUTHOR	Anon.
TITLE	New Ceramic Fiber Assembly Increases Efficiency of Pit-Type Carburizing Furnaces
CITATION	Ind. Heat. v 51 n 4 April 1984 p 28
CATEGORY	ES-C
REMARK	Prefabricated assembly made from vacuum formed ceramic fiber.
ID	42
AUTHOR	Anon.
TITLE	Energy Conservation Program at Forge Shop--A Total Commitment
CITATION	Ind. Heat. v 50 n 7 Jul 1983 p 15
CATEGORY	ES-C
REMARK	Carbottom reheat forge furnaces and heat treating furnaces at Earle M. Jorgensen Co.
ID	43
AUTHOR	Rried, Steven R.
TITLE	Modernization of Rotary Hearth Forge Furnace and Fuel Savings Documented
CITATION	Ind. Heat. v 50 n 7 Jul 1983 p 12
CATEGORY	ES-C
REMARK	Bethlehem Steel Corp.
ID	44
AUTHOR	Anon.
TITLE	Ceramic Fiber Veneering of Reformer Reduces Fuel Used in Ammonia Production By 13%
CITATION	Ind. Heat. v 50 n 3 March 1983 p 32
CATEGORY	ES-C
REMARK	
ID	45
AUTHOR	Anon.
TITLE	Refractory Fiber Modules Efficiently Retrofit Annealing Furnaces of Unusual Design
CITATION	Ind. Heat. v 50 n 3 March 1983 p 30
CATEGORY	ES-C
REMARK	
ID	46
AUTHOR	Anon.
TITLE	Kiln Lining of Fiber Blocks Provides Fuel Savings and Increases Production at Denmark Plant
CITATION	Ind. Heat. v 49 n 10 Oct 1982 p 43
CATEGORY	ES-C
REMARK	Saffil used in a 1500 degree C(2732 degree F) kiln.

ID	47
AUTHOR	Anon.
TITLE	Energy Savings by Modification of Billet and Rail Reheat Furnace
CITATION	Ind. Heat. v 49 n 9 Sept 1982 p 38
CATEGORY	ES-C
REMARK	
ID	48
AUTHOR	Anon.
TITLE	Ceramic Fiber Seals Save Fuel at Bethlehem Steel Mill
CITATION	Ind. Heat. v 49 n 7 Jul 1982 p 38
CATEGORY	ES-C
REMARK	
ID	49
AUTHOR	Anon.
TITLE	Relining of Iron Heat Treating Furnace with Ceramic Fiber Conserves Process Gas
CITATION	Ind. Heat. v 49 n 6 Jun 1982 p 54
CATEGORY	ES-C
REMARK	
ID	50
AUTHOR	Anon.
TITLE	Energy Savings in Heating High Carbon Steels in Slot Forge Furnace
CITATION	Ind. Heat. v 49 n 4 April 1982 p 17
CATEGORY	ES-C
REMARK	
ID	51
AUTHOR	Anon.
TITLE	Ceramic Fiber Lined Electric Furnace Effectively Heats Aircraft and Nuclear Metals for Forging
CITATION	Ind. Heat. v 49 n 1 Jan 1982 p 39
CATEGORY	ES-C
REMARK	
ID	52
AUTHOR	Anon.
TITLE	Vapor Oxidizer Lined with Ceramic Fiber Block Destroys Fumes and Recovers Energy
CITATION	Ind. Heat. v 48 n 11 Nov 1981 p 42
CATEGORY	ES-C
REMARK	
ID	53
AUTHOR	Barrows, Gerald L.
TITLE	Ceramic Fiber vs Insulating Firebrick Furnace Linings in Two Case Studies
CITATION	Ind. Heat. v 48 n 6 Jun 1981 p 42
CATEGORY	ES-C
REMARK	Very useful. Detailed comparison on (1)Heat treating furnace, and (2)Kiln.

ID	54
AUTHOR	Fay, Gordon C.
TITLE	Recirculating Shuttle Kiln Lined with Fiber Refractory Provides High Fuel Efficiency
CITATION	Ind. Heat. v 48 n 4 April 1981 p 29
CATEGORY	ES-F
REMARK	Shuttle kiln.
ID	55
AUTHOR	Anon.
TITLE	Conversion of Furnace for Stress Relieving Castings Saves Energy
CITATION	Ind. Heat. v 47 n 9 Sep 1980 p 38
CATEGORY	ES-C
REMARK	
ID	56
AUTHOR	Anon.
TITLE	Role of Ceramic Fiber Insulation in Recuperating Energy of Steel Plant Annealing Furnace
CITATION	Ind. Heat. v 47 n 9 Sept 1980 p 37
CATEGORY	ES-C
REMARK	
ID	57
AUTHOR	Anon.
TITLE	Remodeling of Pottery Kiln Saves Fuel
CITATION	Ind. Heat. v 47 n 8 Aug 1980 p 41
CATEGORY	ES-C
REMARK	
ID	58
AUTHOR	Anon.
TITLE	Use of Ceramic Fiber in Vacuum Heat Treating Furnaces
CITATION	Ind. Heat. v 47 n 5 May 1980 p 44
CATEGORY	ES-C
REMARK	
ID	59
AUTHOR	Anon.
TITLE	Ceramic Fiber Blanket Reline Halves Fuel Use in Bethlehem Steel Annealing Furnace
CITATION	Ind. Heat. v 47 n 4 April 1980 p 63
CATEGORY	ES-C
REMARK	
ID	60
AUTHOR	Vanderkaay, D. H.
TITLE	Conversion of Furnaces Using Ceramic Fiber Modules and New Electric Heating System
CITATION	Ind. Heat. v 47 n 1 Jan 1980 p 34
CATEGORY	ES-C
REMARK	

ID	61
AUTHOR	Hollander, Frans
TITLE	Reheating processes and modifications to rolling mill operations for energy savings
CITATION	Iron and Steel Engineer June 1983 p 55
CATEGORY	F-O
REMARK	
ID	62
AUTHOR	Anon.
TITLE	Considerations for Energy Savings in Design and Use of Continuous Heat Treating Furnaces Part I -- Role of Controls
CITATION	Ind. Heat. v 48 n 6 June 1981 p 33
CATEGORY	ES
REMARK	This is the first article of a series of three.
ID	63
AUTHOR	Anon.
TITLE	Considerations for Energy Savings in Design and Use of Continuous Heat Treating Furnaces Part II -- Role of Heating Systems
CITATION	Ind. Heat. v 48 n 11 Nov 1981 p 34
CATEGORY	ES
REMARK	Part two of three.
ID	64
AUTHOR	Anon.
TITLE	Considerations for Energy Savings in Design and Use of Continuous Heat Treating Furnaces Part III -- Roles of Insulating Systems and Processing Cycle
CITATION	Ind. Heat. v 49 n 1 Jan 1982 p 40
CATEGORY	ES-F
REMARK	Part three of three.
ID	65
AUTHOR	Turton, Geoff; Argent, Ronald D.
TITLE	Cross-Fired, Multipass Regenerative Furnaces
CITATION	Ceramic Bulletin v 67 n 7 1988 p 1191
CATEGORY	
REMARK	
ID	66
AUTHOR	Anon.
TITLE	How to limit heat loss in a 42-ton holding furnace to 175 kWh per hour
CITATION	DOE Supplement
CATEGORY	
REMARK	
ID	67
AUTHOR	Atterbury, T.
TITLE	Heat treatment plant for tools and dies
CITATION	Metallurgia September 1980 p 438
CATEGORY	
REMARK	

ID	68
AUTHOR	Walker, Allen L.
TITLE	Vacuum heat treatment
CITATION	Metallurgia and Metal Forming September 1974 p 274
CATEGORY	
REMARK	
ID	69
AUTHOR	Fukushima, Takeo
TITLE	Recent Technological Progress in High Speed Continuous Annealing
CITATION	Transactions ISIJ v 25 1985 p 278
CATEGORY	
REMARK	
ID	70
AUTHOR	Anon.
TITLE	Low Cost Investments for Baffled Furnace Users
CITATION	DOE Supplement S33
CATEGORY	
REMARK	
ID	71
AUTHOR	Heilmann, P.
TITLE	Modern Heat-treatment Processes and Systems -- A Review
CITATION	June 1985
CATEGORY	
REMARK	
ID	72
AUTHOR	Sakano, Yoshiro; Takahashi, Hiroshi
TITLE	Outlook for the Refractories Industry in Japan
CITATION	Ceramic Bulletin v 67 n 7 1988 p 1164
CATEGORY	ES
REMARK	
ID	73
AUTHOR	Anon.
TITLE	Effectiveness of Coating Refractories for Energy Savings
CITATION	Ind. Heat. v 49 n 4 April 1982 p 10
CATEGORY	
REMARK	
ID	74
AUTHOR	Caspersen, Lance J.
TITLE	Furnace Veneering Systems of Special Design Help Achieve Energy Reduction Goals at Armco
CITATION	Ind. Heat. v 49 n 12 Dec 1982 p 34
CATEGORY	
REMARK	

ID	75
AUTHOR	Anon.
TITLE	Veneering of Hugh Rotary Reheat Furnace Saves Fuel
CITATION	Ind. Heat. v 51 n 7 July 1984 p 32
CATEGORY	
REMARK	
ID	76
AUTHOR	Vance, M. W.
TITLE	Development of a Non-Welded Skid-Pipe Insulation for Steel Plant Reheat Furnaces
CITATION	Ind. Heat. v 52 n 4 April 1985 p 22
CATEGORY	
REMARK	
ID	77
AUTHOR	Ciliberto, Tony
TITLE	Design and Installation of Layered Ceramic Fiber Modules for Furnace Efficiency
CITATION	Ind. Heat. v 48 n 4 April 1981 p 20
CATEGORY	
REMARK	
ID	78
AUTHOR	West, John
TITLE	Retrofitting Forge Shop Furnaces for Energy Conservation
CITATION	Ind. Heat. v 49 n 7 July 1982 p 26
CATEGORY	
REMARK	
ID	79
AUTHOR	Lasday, Stanley B.
TITLE	Exemplification of Energy Savings in Heat Treating
CITATION	Ind. Heat. v 47 n 8 Aug 1980
CATEGORY	
REMARK	
ID	80
AUTHOR	Hamling, Philip
TITLE	1700C Rapid Cycle Furnace Insulation Design Part I - Ceramic Fiber Properties
CITATION	Ind. Heat. v 55 n 4 April 1988 p 30
CATEGORY	ES-F
REMARK	Useful. Part one of a series of two.
ID	81
AUTHOR	Hamling, Philip
TITLE	1700C Rapid Cycle Furnace Insulation Design Part II - Chamber Design
CITATION	
CATEGORY	
REMARK	

ID	82
AUTHOR	Thomas, Everett E.; Ford, James M.; Zingel, Gerhard
TITLE	Basic Refractories as Related to Ladle Metallurgy
CITATION	Ind. Heat. v 50 n 3 March 1983 p 10
CATEGORY	
REMARK	
ID	83
AUTHOR	Jayaraman, V.
TITLE	New Ceramic Radiant Tube Fired Forging Furnaces Reduces Scale and Increases Fuel Efficiency
CITATION	Ind. Heat. v 48 n 4 April 1981 p 17
CATEGORY	
REMARK	
ID	84
AUTHOR	Anon.
TITLE	Continuous Annealing Furnace Heat Recovery for Direct Preheating of Steel Strip and Space Heating
CITATION	Ind. Heat. v 48 n 8 Aug 1981 p 22
CATEGORY	
REMARK	
ID	85
AUTHOR	Casper. Stanley E.
TITLE	Design of Vacuum Furnace and its Significance in Heat Treating Forgings
CITATION	Ind. Heat. v 48 n 9 September 1981 p 45
CATEGORY	
REMARK	
ID	86
AUTHOR	Casana, A.; Stabile, V.
TITLE	Continuous Walking Beam Furnace Facility -- Design Aspects and Operating Data for Heat Treating Cylinders: II
CITATION	Ind. Heat. v 50 n 10 Oct 1983 p 42
CATEGORY	
REMARK	
ID	87
AUTHOR	Anon.
TITLE	Cement Lining of Induction Furnace for Tungsten Carbide Production
CITATION	Ind. Heat. v 48 n 3 March 1981 p 42
CATEGORY	
REMARK	
ID	88
AUTHOR	Anon.
TITLE	Easily-Handled Insulation Speeds Installation and Reduces Refractory Grog Loss in Waste Heat Conduit
CITATION	Ind. Heat. v 47 n 5 May 1980 p 47
CATEGORY	
REMARK	

ID	89
AUTHOR	Anon.
TITLE	Drying, Baking and Curing of Metal Coatings in Versatile, Continuous Gas-Fired Oven
CITATION	Ind. Heat. v 47 n 6 June 1980 p 37
CATEGORY	
REMARK	
ID	90
AUTHOR	Anon.
TITLE	Mesh Belt Furnace Design Expands Heat Treat Shop's Capability
CITATION	Ind. Heat. v 47 n 8 Aug 1980 p 44
CATEGORY	
REMARK	
ID	91
AUTHOR	Anon.
TITLE	Electric Furnace with MoSi ₂ Elements Efficiently Used in Atmosphere Heat Treating of Farm Machinery Parts
CITATION	Ind. Heat. v 47 n 12 Dec 1980 p 18
CATEGORY	
REMARK	
ID	92
AUTHOR	Anon.
TITLE	Induction and Fuel Fired Furnaces Combined for More Effective Heat Treatment of Oil Country Tubulars
CITATION	Ind. Heat. v 47 n 11 Nov 1980 p 21
CATEGORY	
REMARK	
ID	93
AUTHOR	Kuhn, Friedhelm
TITLE	Energy Situation in Europe and Conservation in Some Industrial Furnace Uses
CITATION	Ind. Heat. v 50 n 11 Nov 1983 p 25
CATEGORY	
REMARK	
ID	94
AUTHOR	Anon.
TITLE	Design and Economical Operation of Carbon Reactivation Furnaces
CITATION	Ind. Heat. v 52 n 4 April 1985 p 45
CATEGORY	
REMARK	
ID	95
AUTHOR	Anon.
TITLE	Expanded Heat Treating Facilities for Steel Mill Products at TC Industries, Inc.
CITATION	Ind. Heat. v 48 n 7 July 1981 p 48
CATEGORY	
REMARK	

ID	96
AUTHOR	Anon.
TITLE	New Box Furnace Line and Stacker Crane Increases Capability at Heat Treat Shop
CITATION	Ind. Heat. v 48 n 7 July 1981
CATEGORY	
REMARK	
ID	97
AUTHOR	Willett, Gordon H.
TITLE	Energy Savings and Efficiency in Design of Continuous Hardening Furnace
CITATION	Ind. Heat. v 51 n 8 Aug 1984 p 22
CATEGORY	
REMARK	
ID	98
AUTHOR	McMaster, Ronald A.
TITLE	Electrically Heated Furnaces Used in Glass Tempering Systems
CITATION	Ind. Heat. v 82 n 4 April 1985 p 46
CATEGORY	
REMARK	
ID	99
AUTHOR	E. M. Dickson
TITLE	Ceramic Fibres---a growing refractory product
CITATION	TN677.5 R3 1981 REF (CSM Library)
CATEGORY	
REMARK	From an industrial report, which contains more useful informations: RAW MATERIALS FOR THE REFRACTORIES INDUSTRY TN677.5 R3 1981 (CSM Library)
ID	100
AUTHOR	Anon
TITLE	Study of furnaces lined with ceramic fibre
CITATION	Iron Steel Int v 47 n 2 Apr 1974 p 145-146
CATEGORY	
REMARK	K16
ID	101
AUTHOR	Fletcher, J. D.; William, Alan
TITLE	Emissivities of Ceramic fibre linings for high-temperature furnaces
CITATION	Journal of the Institute of Energy v 57 n 432 Sep 1984 p 377
CATEGORY	
REMARK	K6
ID	102
AUTHOR	Anon
TITLE	Nature of New Ceramic Fiber Insulation System that Resists Temperatures to 3000F
CITATION	Industrial Heating v 47 n 12 Dec 1980 p 28-29
CATEGORY	
REMARK	K10

ID	103
AUTHOR	Anon
TITLE	Installation and Economy of Ceramic Fiber Roofs for Forge Furnaces
CITATION	Industrial Heating v 43 n 4 Apr 1976 p 33-34, 36-37
CATEGORY	
REMARK	K12
ID	104
AUTHOR	Anon
TITLE	High Temperature Ceramic Fiber Effective in Insulating Wire Uses
CITATION	Industrial Heating v 49 n4 April 1982 p24
CATEGORY	
REMARK	IH1
ID	105
AUTHOR	Copes, Jane Snell; Smith, Robert G.
TITLE	Microstructural Characterization of Thermally-Aged Siconex Oxide Fiber/SiC Composite Materials
CITATION	Ceram. Eng. Sci. Proc., 8[7-8] p. 976 (1987)
CATEGORY	
REMARK	N12 Materials Science
ID	106
AUTHOR	D. D. Johnson, A. R. Holtz, M. F. Grether
TITLE	Properties of Nextel 480 Ceramic Fibers
CITATION	Ceram. Eng. Sci. Proc., 8[7-8] pp. 744-754 (1987)
CATEGORY	
REMARK	N13 Materials Science
ID	107
AUTHOR	Harold G. Sowman
TITLE	A New Era in Ceramic Fibers via Sol-Gel Technology
CITATION	Ceramic Bulletin, Vol 67, No. 12, 1988
CATEGORY	
REMARK	N4 S5 Materials Science
ID	108
AUTHOR	M. H. Stacey
TITLE	Developments in Continuous Alumina-Based Fibres
CITATION	Br. Ceram. Trans. J., 87, 168-172, 1988
CATEGORY	
REMARK	N5 S6 Materials Science
ID	109
AUTHOR	S. Karlsson, R. Lundberg, R. Carlsson
TITLE	Thermal and Environmental Effects on Ceramic Fibers
CITATION	J. de Physique Colloque C1 suppl v 47 n2 Fem 1986 p 587-591
CATEGORY	
REMARK	S13 Materials Science

ID	110
AUTHOR	Anon
TITLE	Why a high alumina fibre lining can be money well spent
CITATION	Iron and Steel International v 53 n 2 Apr 1980 p105-106
CATEGORY	
REMARK	S22
ID	111
AUTHOR	T. Kokubo, Y. Teranishi, T. Maski, S. Sakka
TITLE	Formation of Zirconia fibres on unidirectional freezing of a gel
CITATION	Journal of Materials Science 23 (1988) 1126-1130
CATEGORY	
REMARK	Z15 Materials Science
ID	112
AUTHOR	Sivananda S. Jada
TITLE	Surface properties of gel-derived zirconia fibres
CITATION	Journal of Materials Science Letters 6 (1987) 1368-1370
CATEGORY	
REMARK	Z17 Materials Science
ID	113
AUTHOR	James C. Romine
TITLE	New High-Temperature Ceramic Fiber
CITATION	Ceram. Eng. Sci. Proc., 8[7-8] pp. 755-765 (1987)
CATEGORY	
REMARK	Z30 Materials Science
ID	114
AUTHOR	David B. Marshall, F. F. Lange, Peter D. Morgan
TITLE	High-Strength Zirconia Fibers
CITATION	J. Am. Ceram. Soc. v 70 n 8 Aug 1987 p C187-C188
CATEGORY	
REMARK	Z32 Materials Science
ID	115
AUTHOR	L. K. Matthews, R. Viskanta, F. P. Incropera
TITLE	Development of Methods for Determining Thermophysical and Radiative Properties of High-temperature Fibrous Materials
CITATION	Int. J. Heat Mass Transfer. v 27 n 4 p 487-495, 1984
CATEGORY	
REMARK	Z79
ID	116
AUTHOR	J. D. Birchall
TITLE	The Preparation and Properties of Polycrystalline Aluminium Oxide Fibres
CITATION	Proc. Br. Ceram. Soc., 33(Fabr. Sci. 3), 51-62
CATEGORY	
REMARK	Materials Science

ID	117
AUTHOR	J. A. Pask, X. W. Zhang, A. P. Tomsia
TITLE	Effect of Sol-Gel Mixing on Mullite Microstructure and Phase Equilibria in the (α - Al_2O_3)- SiO_2 System
CITATION	J. Am. Ceram. Soc., 70[10] 704-707 (1987)
CATEGORY	
REMARK	Materials Science
ID	118
AUTHOR	Kutzendorfer, Jaroslav; Videnska, M.; Zaludova, V; Nemec, L.
TITLE	Shrinkage of refractory fibers
CITATION	Stavivo, 66(7-8), 280-2
CATEGORY	
REMARK	Materials Science In Czech. We have translated the complete article into English.
ID	119
AUTHOR	Ruppelt, Regine
TITLE	Crystallization behavior of aluminosilicate fibers at different temperatures
CITATION	Silikattechnik, 34(2), 58-60
CATEGORY	
REMARK	Materials Science. Language: German. This is one of the only three journal articles that studies the effect of Cr_2O_3 in the devitrification behavior of aluminosilicate fibers. The other articles(ID#: 120, 121) are in German and French. No translations for these articles yet, as of today(12/18/90).
ID	120
AUTHOR	Schulle, Wolfgang; Ruppelt, Regine; Toeppler, Bernd
TITLE	Effect of chromium(III) oxide addition on the thermal behavior of aluminosilicate refractory fibers.
CITATION	Silikattechnik, 37(11), 377-80
CATEGORY	
REMARK	Materials Science. Language: German. One of three articles on the effect of Cr_2O_3 on refractory aluminosilicate fiber. Not translated.
ID	121
AUTHOR	B. Courier, C. Gleitzer, G. Poirson, L. Sebillaud
TITLE	Etude de la recristallisation de fibres refractaires (A study of the recrystallization of refractory fibers)
CITATION	Rev. Int. Hautes Temp. Refract., 19(1), 9-17
CATEGORY	
REMARK	Materials Science. Language: French One of three articles on Cr_2O_3 in refractory fiber. Not translated.
ID	122
AUTHOR	Gaodu, A. N.; Pitak, N. V.; Vol'fson, R. E.; Drizheruk, M.
TITLE	Crystallization in Heated Aluminosilicate Fibers
CITATION	Izv. Akad. Nauk SSSR, Neorg. Mater., 13(12), 2265-8
CATEGORY	
REMARK	Materials Science. This article is a classic on the devitrification of aluminosilicate refractory fibers during heating. We have the English translation.

ID	123
AUTHOR	S. M. Ohlberg, D. W. Strickler
TITLE	Determination of Percent Crystallinity of Partly Devitrified Glass by X-Ray Diffraction
CITATION	J. Am. Ceram. Soc., 45 [4] 170-71 (1962)
CATEGORY	
REMARK	Materials Science. % crystallinity of partly devitrified glass = $100(I-I')/(I-I'')$ Applicable when the normalized amorphous profile is unchanged.
ID	124
AUTHOR	C. Mai, H. Satha, G. Thollet, G. Vigier
TITLE	SAXS, WAXD and TEM of the Early Stages of Crystallization in TiO ₂ -ZrO ₂ -MgO-Li ₂ O-Al ₂ O ₃ -SiO ₂ Glass
CITATION	Journal of Non-Crystalline Solids 108 (1989) 201-206
CATEGORY	
REMARK	Materials Science. SAXS and TEM on glass.
ID	125
AUTHOR	P. Pernice, A. Aronne, A. Costantini, A. Marotta
TITLE	Crystal Nucleation and Growth in an LiNaSiO ₃ Glass
CITATION	Thermochimica Acta, 159 (1990) 299-304
CATEGORY	
REMARK	Materials Science
ID	126
AUTHOR	Guy E. Rindone
TITLE	Further Studies of the Crystallization of a Lithium Silicate Glass
CITATION	J. Am. Ceram. Soc. v 45 n 1 Jan p 7-12 (1962)
CATEGORY	
REMARK	Materials Science
ID	127
AUTHOR	Charles L. Booth, Guy E. Rindone
TITLE	Surface Nucleation and Crystal Orientation in Lithium Silicate Glass Fibers
CITATION	J. Am. Ceram. Soc. v 47 n 1 Jan p 25-29 (1964)
CATEGORY	
REMARK	Materials Science
ID	128
AUTHOR	Biao Yuan, Quan-Qing Chen, Min-Quan Wang
TITLE	Crystallization and properties of Li-Al-B-Ti-silicate system glass-ceramic fibres
CITATION	J. Materials Science 24 (1989) 4488-4494
CATEGORY	
REMARK	Materials Science. Glass-ceramic fibres are studied with DTA, XRD, TEM, and SEM. Sizes of microstructure and surface microcracks are examined.
ID	129
AUTHOR	Zou, Xuelu; Yamane, Masayuki; Li, Jiazhi; Wang, Chengyu
TITLE	Effect of Phase Separation on Nucleation and Growth of Magnesium-Aluminium-Titanate Crystals in MgO-Al ₂ O ₃ -SiO ₂ -TiO ₂ Glass
CITATION	J. Non-Crystalline Solids 112 (1989) 268-271
CATEGORY	
REMARK	Materials Science. SAXS is used.

ID	130
AUTHOR	J. W. Cahn, R. J. Charles
TITLE	The initial stages of phase separation in glasses
CITATION	Physics and Chemistry of Glasses v 6 n 5 October 1965
CATEGORY	
REMARK	Materials Science. Theoretical treatment of phase separation from a single phase is given for both the cases of (1) spinodal decomposition, and (2) nucleation and growth.
ID	131
AUTHOR	Joseph J. Hammel
TITLE	Direct Measurement of Homogeneous Nucleation Rates in a Glass-Forming System.
CITATION	The Journal of Chemical Physics v 46 n 6 March p 2234-2244
CATEGORY	
REMARK	Materials Science.
ID	132
AUTHOR	John W. Cahn
TITLE	Coherent Fluctuation and Nucleation in Isotropic Solids
CITATION	Acta Metallurgica v 10 October p 907-913 (1962)
CATEGORY	
REMARK	Materials Science. On the theory of spinodal decomposition. The author suggested the theoretical understanding of spinodal decomposition in an earlier publication: Acta Metallurgica, 9, 795 (1961)
ID	133
AUTHOR	J. Zarzycki, F. Naudin
TITLE	Spinodal Decomposition in the B ₂ O ₃ -PbO-Al ₂ O ₃ System.
CITATION	J. Non-Crystalline Solids 1 (1969) 215-234
CATEGORY	
REMARK	Materials Science. Experimental verification of spinodal decomposition with SAXS.
ID	134
AUTHOR	G. F. Neilsen
TITLE	Spinodal decomposition in soda-silica glass
CITATION	Physics and Chemistry of Glasses v 10 n 2 April 1969
CATEGORY	
REMARK	Materials Science. The early and later stage kinetics of phase separation in the region of spinodal decomposition in the Na ₂ O-SiO ₂ system are studied with SAXS, in conjunction with electron microscopy. Agreement with various aspects of spinodal theory is obtained.
ID	135
AUTHOR	Fan Dongli
TITLE	Conserving Energy in Heat Treatment in China
CITATION	Industrial Heating v 51 n 7 July p 12-16 (1984)
CATEGORY	
REMARK	
ID	136
AUTHOR	G. M. Workman, I. S. Kessell
TITLE	Steelplant Refractories Face Challenging Future
CITATION	Ind. Heating v 48 n 4 April p 8 (1981)
CATEGORY	
REMARK	

ID	137
AUTHOR	Richard J. Reed
TITLE	Fuel Saving Ideas for Metal and Ceramic Processing
CITATION	Ind. Heating v 50 n 7 July p 8 (1983)
CATEGORY	
REMARK	
ID	138
AUTHOR	Gordon H. Willett
TITLE	Energy Savings and Efficiency in Design of Continuous Hardening Furnace
CITATION	Ind. Heating v 51 n 8 Aug p 22 (1984)
CATEGORY	
REMARK	
ID	139
AUTHOR	John L. Ferri, Kent H. Kohnken
TITLE	Calculation of Fuel Savings via Recuperation by Utilizing Computer Generated Heat Curves
CITATION	Ind. Heating v 51 n 4 April p 40 (1984)
CATEGORY	
REMARK	
ID	140
AUTHOR	Win Irwin
TITLE	How Thick Should Insulation Be on Hot Tanks
CITATION	Ind. Heating v 51 n 4 April p 42 (1984)
CATEGORY	
REMARK	
ID	141
AUTHOR	Thomas Foust
TITLE	Graphical Analysis for Determination of Fuel Savings
CITATION	Ind. Heating v 46 n 7 July p 10 (1979)
CATEGORY	
REMARK	
ID	142
AUTHOR	James G. Floor
TITLE	How to Conduct an Energy Audit & Conservation Program
CITATION	Ind. Heating v 46 n 7 July p 6 (1979)
CATEGORY	
REMARK	
ID	143
AUTHOR	D. A. Zurawaki
TITLE	Heat Balances and Fuel Conservation of Thermally-Aged Siconex Oxide Fiber/SiC Composite Materials
CITATION	Ind. Heating v 48 n 6 June p 8 (1981)
CATEGORY	
REMARK	

ID	144
AUTHOR	J. J. Marino
TITLE	Thermal Design of Refractory and Insulating Systems Part I -- Mechanism of Heat Transfer
CITATION	Ind. Heating v 47 n 5 May p 6 (1980)
CATEGORY	
REMARK	Part 1 of 8
ID	145
AUTHOR	J. J. Marino
TITLE	Thermal Design of Refractory and Insulation Systems Part II -- Heat Transfer Through Refractory-Insulating Systems
CITATION	Ind. Heating v 47 n 6 June p 44 (1980)
CATEGORY	
REMARK	Part 2 of 8
ID	146
AUTHOR	J. J. Marino
TITLE	Thermal Design of Refractory and Insulating Systems Part III -- Resistance Graph Use in Optimum Lining
CITATION	Ind. Heating v 47 n 7 July p 38 (1980)
CATEGORY	
REMARK	Part 3 of 8
ID	147
AUTHOR	J. J. Marino
TITLE	Thermal Design of Refractory and Insulating Systems Part IV -- Relating Resistance and Environmental Conditions to Heat Loss
CITATION	Ind. Heating v 47 n 8 August p 35 (1980)
CATEGORY	
REMARK	Part 4 of 8
ID	148
AUTHOR	J. J. Marino
TITLE	Thermal Design of Refractory and Insulating Systems Part V -- Thermal Effect of Roof & Bottom of Furnace
CITATION	Ind. Heating v 47 n 10 Oct p 38 (1980)
CATEGORY	
REMARK	Part 5 of 8
ID	149
AUTHOR	J. J. Marino
TITLE	Thermal Design of Refractory and Insulating Systems Part VI -- Variable Most Affecting Lining Design
CITATION	Ind. Heating v 47 n 11 Nov p 44 (1980)
CATEGORY	
REMARK	Part 6 of 8
ID	150
AUTHOR	J. J. Marino
TITLE	Thermal Design of Refractory and Insulating Systems Part VII -- Design Trap: Unusual Environmental Conditions
CITATION	Ind. Heating v 47 n 12 Dec p 32 (1980)
CATEGORY	
REMARK	Part 7 of 8

ID	151
AUTHOR	J. J. Marino
TITLE	Thermal Design of Refractory and Insulating Systems Part VIII -- Fixed Wall Dimensions
CITATION	Ind. Heating v 48 n 1 Jan p 35 (1981)
CATEGORY	
REMARK	Part 8 of 8
ID	152
AUTHOR	Harry E. Trout
TITLE	Refractories: An Overview Part I -- History
CITATION	Ind. Heating v 50 n 2 Feb p 52 (1983)
CATEGORY	
REMARK	Part 1 of 5
ID	153
AUTHOR	Harry E. Trout
TITLE	Refractories: An Overview Part II -- Silica Materials, Fireclays
CITATION	Ind. Heating v 51 n 2 Feb p 54 (1984)
CATEGORY	
REMARK	Part 2 of 5
ID	154
AUTHOR	Harry E. Trout
TITLE	Refractories: An Overview Part III -- High Alumina
CITATION	Ind. Heating v 51 n 3 March p 40 (1984)
CATEGORY	
REMARK	Part 3 of 5
ID	155
AUTHOR	Harry E. Trout
TITLE	Refractories: An Overview Part IV -- Basic Refractories
CITATION	Ind. Heating v 51 n 4 April p 14 (1984)
CATEGORY	
REMARK	Part 4 of 5
ID	156
AUTHOR	Harry E. Trout
TITLE	Refractories: An Overview Part V -- Some Special Types
CITATION	Ind. Heating v 51 n 9 Sept p 36 (1984)
CATEGORY	
REMARK	Part 5 of 5
ID	157
AUTHOR	R. Ganz, W. Kronert
TITLE	Crystallisation Behavior of High Temperature Ceramic Fibers of the Al ₂ O ₃ -SiO ₂ System
CITATION	INTERCERAM NR.2, 1982
CATEGORY	
REMARK	Materials Science. This is the only paper written in ENGLISH that studies the products of devitrification quantitatively. The other articles we have in possession are either in German or French. Presented at the XXIVth International Colloquium on Refractories, Aachen (Fed. Rep. Germany), Sept. 24-25, 1981.

ID	158
AUTHOR	D. G. LeGrand
TITLE	Small-Angle X-Ray and Neutron Scattering
CITATION	
CATEGORY	
REMARK	Materials Science. A concise discussion of SAXS, with references.

ID	159
AUTHOR	Jerome D. Wisnosky, Raymond C. Kent
TITLE	Techniques for Testing the Refractory Behaviour of Inorganic Fiber
CITATION	Am. Ceram. Soc. Bulletin v 55 n 11 p 989 (1976)
CATEGORY	
REMARK	Materials Science.

ID	160
AUTHOR	B. A. Scowcroft, G. C. Padgett
TITLE	3. -- The Structure and Thermal Behaviour of Ceramic Fibre Blankets
CITATION	Trans. Br. Ceram. Soc. v 72 p 11-14 (1973)
CATEGORY	
REMARK	Materials Science.

ID	161
AUTHOR	A. E. Pickles, E. Norcross
TITLE	38. -- Lightweight Kilns - A New Development
CITATION	Trans. Br. Ceram. Soc. v 73 p 239 (1974)
CATEGORY	
REMARK	Materials Science.

APPENDIX A.2
X-RAY DIFFRACTION PATTERNS AFTER HEAT TREATMENT

KAOWOOL 2600 - AFTER 24 HOURS @ 2600°F

KAOWOOL 2600 - AFTER 168 HOURS @ 2600°F

KAOWOOL ZR - AS RECEIVED

KAOWOOL ZR - AFTER 4 HOURS @ 2600°F

CERACHROME - AS RECEIVED

CERACHROME - AFTER 4 HOURS @ 2600°F

CERACHROME - AFTER 24 HOURS @ 2600°F

CERACHROME - AFTER 168 HOURS @ 2600°F

FIBERMAX - AFTER 24 HOURS @ 2600°F

FIBERMAX - AFTER 168 HOURS @ 2600°F

SAFFIL - AS RECEIVED

SAFFIL - AFTER 4 HOURS @ 2600°F

SAFFIL - AFTER 24 HOURS @ 2600°F

SAFFIL - AFTER 168 HOURS @ 2600°F

APPENDIX A.3
SEM VIEWS AFTER HEAT TREATMENT AT 2600°F

SEM-18394 KAOWOOL 2600 4HRS@2600°F 1000X

SEM-18395 KAOWOOL 2600 4 HR@2600°F 10000X

SEM-18404 KAOWOOL 2600 24HR@2600°F 1000X

SEM-18405 KAOWOOL 2600 24HR@2600°F 10000X

SEM-18731 KAOWOOL 2600 168HR@2600°F 1000X

SEM-18732 KAOWOOL 2600 168HR@2600°F 10000X

SEM-18386 KAOWOOL ZR AS RECEIVED 1000X

SEM-18387 KAOWOOL ZR AS RECEIVED 10000X

SEM-18396 KAOWOOL ZR 4HR@2600°F 1000X

SEM-18397 KAOWOOL ZR 4HR@2600°F 10000X

SEM-18406 KAOWOOL ZR 24HR@2600°F 1000X

SEM-18407 KAOWOOL ZR 24HR@2600°F 10000X

SEM-18733 KAOWOOL ZR 168HR@2600°F 1000X

SEM-18734 KAOWOOL ZR 168HR@2600°F 10000X

SEM 18388 CERACHROME AS RECEIVED 1000X

SEM 18389 CERACHROME AS RECEIVED 10000X

SEM 18398 CERACHROME 4HR@2600°F 1000X

SEM 18399 CERACHROME 4HR@2600°F 10000X

SEM-18408 CERACHROME 24HR@2600°F 1000X

SEM-18409 CERACHROME 24HR@2600°F 10000X

SEM-18737 FIBERMAX 168HR@2600°F 10000X

SEM-18738 FIBERMAX 168HR@2600°F 10000X

SEM-18412a SAFFIL 24HR@2600°F 1000X

SEM-18412b SAFFIL 24HR@2600°F 10000X

END

**DATE
FILMED**

12130191