**PRODUCT TECHNOLOGY AND MARKET ASSESSMENT FOR
SILICON CARBIDE WHISKER REINFORCED ALUMINA
HEAT-EXCHANGER TUBES**

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ABSTRACT

This report describes a study designed to develop an assessment of key performance features, desirable technical specifications and market potential for silicon carbide whisker-reinforced alumina (henceforth SCWRA) tubes for heat exchanger applications in a number of industries. The results of the first stage of a Delphi study conducted in the U.S. market are presented. The second phase of the study is in progress.

The first stage results suggest that there is a small market for SCWRA tubes in heat exchanger applications. The market is expected to grow steadily during the 1990's. With appropriate performance specifications and competitive pricing, growth should come from (a) new applications that permit recovery in cases that were previously infeasible and (b) selective, partial substitution and replacement of current ceramics and metal/ceramic composites in existing applications.

We identify key performance factors and detailed specifications needed in six designated industries (primary metals, fabricated metals, chemicals, glass, utility and incinerators). Reliability, durability and low maintenance costs emerge as critical performance factors across these industries. The data show that although ceramics are recognized as having better properties, enhancing reliability and durability and thus improving maintenance cost performance is a key priority. Such improvements, reflected in the objectives for SCWRA tubes, should facilitate adoption in both new and existing applications.

At this time, we are unable to assess market size directly. However, expert judgment provided indices tracking the projected market for heat exchanger tubes from 1990 to 2005.

A Frost and Sullivan report estimated the total heat-exchanger shell and tube sales in 1990 to be \$821 million. Assuming that tubes comprise 50% of the total shell and tube sales, the base total market was estimated at \$582 million in 1995, \$867 million in 2000 and \$1251 million in 2005. The introduction of SCWRA tubes is expected to expand the market to \$593 million, \$921 million and \$1419 million in these years. Metals, (currently 87% share) were expected to drop progressively to 81%, 75% and 69% respectively. Ceramics and composites were expected to post corresponding gains. Specifically, the estimated market share of SCWRA tubes was 5.0%, 6.6% and 7.6%, translating to most likely estimated sales volumes of \$30 million, \$61 million and \$108 million in 1995, 2000 and 2005, respectively.

BACKGROUND

Although heat exchangers have been used in a variety of industrial processes for over sixty years, their performance and market acceptance continues to be limited by technical problems. The problems are very severe in industrial environments where high temperature capability and high corrosion resistance are essential. As Richlen (1985) suggests, for a heat exchanger manufactured from carbon steel, the bulk material temperature should not exceed 800°F. At temperatures higher than 1200°F, corrosion resistance and strength become significant limitations for higher performance stainless steels. Though dilution of hot gases is a solution, this significantly degrades heat quality and reduces efficiency of the heat transfer process. Hence, to improve heat exchanger performance in high temperature and highly corrosive environments, research and development has focused on replacing the heat exchanger's vulnerable components with either high temperature metallics or ceramics.

Recent studies (Foster and Patton 1985, Mueller Associates 1987) show that significant energy savings could result from waste heat recovery efforts (i.e., recuperators) in the primary metal (e.g., steel, aluminum) and glass industries. Although silicon carbide (SiC) is often the material of choice, it is rapidly attacked by the constituents of the waste heat stream. Alumina (Al_2O_3) is far more corrosion resistant in such environments. Yet, its poor thermal shock resistance makes it unacceptable as heat-exchanger tube material.

Studies at the Oak Ridge National Laboratories (see Tiegs and Becher 1987; Janney, Bomar and Vance 1989) show that silicon carbide whisker-reinforced alumina (SCWRA) composites are excellent as recuperator tube material because they possess both high strength (up to 1850°F) and improved thermal shock resistance compared to normal alumina. Moreover, recent industrial furnace exposure tests have shown that SCWRA has very similar corrosion resistance to pure alumina under conditions that are extremely corrosive to pure SiC.

Steam reforming of natural gas is used in many industrial settings to produce hydrogen for either on site use or for sale. The primary reaction occurs in convective reformer tubes in specialized fired heaters, typically at 1380 to 1560°F and at pressures of 415 to 515 psi. The primary reaction is highly endothermic and is favored by high temperatures and low pressures. Hence, there is significant potential for energy and cost savings if the reformer tube could withstand such pressure and temperature.

The technology is mature and unlikely to improve greatly with current materials. Replacing current metal reformer tubes with SCWRA tubes may have several advantages. Higher temperatures would increase yield. Also, new tubes with higher temperature capabilities would allow reforming at higher natural gas supply pressures (e.g., 1000 psi) with the same yield,

reducing compression costs. The possibility of retrofit applications will also improve the rate of implementation. The key application areas for gauging the commercialization and energy savings potential of this concept includes petroleum refining, ammonia production and methanol manufacture.

Significant energy savings may also be achieved by developing advanced high temperature indirect natural-gas fired heating systems. Electric heating is widely used in such high temperature processes as sintering, carburizing, brazing, stainless steel annealing and vacuum heat treating. These processes need precise temperature and compositional control of the furnace atmosphere and natural gas is a viable alternative in such applications if an efficient indirect heating system may be found.

The critical component of such a system is the radiant tube which provides the required heat transfer service and has the required resistance to the combustion flame and to its oxidizing by-products. There is a need for reliable, and low maintenance cost radiant tubes for advanced indirect heating systems. By virtue of its thermal and mechanical properties SCWRA would be an excellent candidate material for such radiant tubes.

PURPOSE OF STUDY

Martin Marietta Energy Systems Inc., (under contract #DE-AC05-84OR21400) with Department of Energy (DOE) Office of Industrial Programs, sponsored a program (Contract #5101-90-10) with Materials and Electrochemical Research (MER) Corporation to develop manufacturing capabilities for fabricating large-diameter whisker-reinforced alumina tubes. MER Corporation has conducted fourteen ceramic whiskers development programs, including five $\text{Al}_2\text{O}_3\text{-SiC}_w$ programs. On the technical side, MER Corporation is working with Vesuvius-McDanel to develop the fabrication process. Vesuvius-MacDanel is the largest U.S. supplier (second in the world) of monolithic ceramic tubes, including four alumina tube products. The companies will jointly develop the forming and sintering technologies to produce the high performance, low cost SCWRA tubes. Commercially viable scale-up technologies are being employed to achieve the desirable performance and cost goals.

Despite the technical possibilities for successful development, there is little hard knowledge available to guide a product development and market analysis process at this time. Therefore, the current program also has the objective of developing a realistic assessment of the desirable technical features as well as the market potential for SCWRA tubes for use in heat exchangers. MER Corporation therefore approached the University of Arizona, Department of Marketing for help with a market study. The study was subcontracted to, and performed under the supervision of, Dr. Dipankar Chakravarti, Head of the Department of Marketing, Karl Eller Graduate School of Management, University of Arizona.

Based upon consultation among representatives from MER Corporation, Vesuvius-MacDanel and DOE, the present study set four objectives:

1. To assess the important performance factors for SCWRA tubes in specific industries;
2. To develop the detailed performance specifications for heat exchanger tubes by these specific industries;
3. To assess the degree to which SCWRA tubes may substitute and replace other heat exchanger tube materials and to identify the key barriers and facilitators to such replacement/substitution; and
4. To assess the current market potential and the projected market development scenario for the product.

METHODOLOGY

A fragmented marketplace and an uncertain technology makes it difficult to tap published secondary data for meeting study objectives. It was therefore decided that a modified Delphi survey would be used to collect the data. The Delphi technique (developed by the Rand Corporation in 1948) is an iterative process that pools judgments of selected experts in the field through several rounds of written questionnaire-based surveys. The experts are given intensive questionnaires along with controlled opinion feedback to drive toward consensus on a judgment. The method is widely used in forecasting (see Kudon and Frankel 1989; Snizek 1989) and has been applied successfully in technology forecasting studies similar to this one (Larsen and Vyas 1988).

The present report summarizes the results from the first stage of the ongoing Delphi study. As such, the data do not reflect the consensus attainment process that characterizes a normal Delphi survey. Rather, they should be viewed as an initial summary of the judgments of a set of expert respondents who responded to our solicitation of their participation in the first stage survey. Hence these results have the status of a standard market survey done with a convenience sample of respondents. The formal features of a modified Delphi study will be met once the second phase is completed.

The first stage questionnaire (Appendix A) was developed over several months. It was pretested twice with the help of the technical consultants who were representatives of Vesuvius/McDanel, Oak Ridge National Laboratory and six other carefully selected pretest respondents. The result was a survey that explored the issues at length and solicited open-ended comments and explanations as appropriate or necessary.

The pretest survey was in four parts. In Part A, the questions were designed to elicit respondents' perceptions of the relative importance of some performance factors that may be used to evaluate and select heat-exchanger tubes in a number of industries. The fifteen performance factors were selected by careful consideration of likely critical attributes and the six industries were chosen on the basis of client interest. Respondents could provide data on one additional industry and also add new performance factors for each industry as needed. An open ended question allowed additional qualitative commentary.

Part B was the lengthiest section of the questionnaire. It dealt with the respondents' assessments of the desirable performance specifications for heat exchanger tubes in each of the industries in Part A. At the start of this section, respondents self-rated their familiarity with each industry. This was done so that the results could be developed based only on the responses of

the relatively more knowledgeable respondents for each industry. This impacted the number of respondents for each question but plausibly improved data quality and meaningfulness.

Part C aimed at eliciting the degree to which respondents felt that SCWRA tubes would replace or substitute other currently used heat exchanger tube material. One set of questions dealt with the perceptions of current usage of various materials. In another set, a technical description of the proposed SCWRA tube material was provided along with reference prices. Respondents then indicated the likelihood of substitution and replacement by alternative heat exchanger tube material and by industry. These questions helped calibrate price elasticity. Finally, respondents rated various performance factors of the SCWRA tube in terms of being barriers or facilitators to adoption.

The final section, Part D, asked respondents for estimates of the current market potential and the projected rate of market development. The questions asked for estimates of market volume, share and growth by industry and material, both with and without the introduction of the SCWRA tubes. This section also included questions designed to classify the respondent by personal and professional characteristics.

THE FIRST STAGE SURVEY RESPONSE

Given the uncertainty regarding an appropriate sampling frame of potential expert respondents, it was decided that a convenience sample would be used for this study. A mailing list was generated by pooling names of from a customer list provided by Vesuvius/MacDanel, a list of authors and practitioners in the relevant field, and a list of university professors and other miscellaneous experts provided by the Oak Ridge National Laboratory. The pooled list had 374 names and each of these potential experts was sent the questionnaire along with a covering letter (Appendix A). Only domestic listings were contacted. The respondents were guaranteed confidentiality of their individual responses and were offered a copy of the final report as an incentive for their participation.

The first mailing produced a total of 62 responses of which 27 were usable. A key subset of 64 of the 312 nonrespondents were mailed the questionnaire once again and also contacted by phone. This second mailing and follow-up produced another 20 responses of which 12 were usable. The mailings and follow-up produced a 22 percent response rate and a usable response rate of slightly over 10%. This is viewed as acceptable given the initial uncertainty regarding the appropriate population and the decision to use the extensive questionnaire.

Table 1 profiles respondents in terms of age, education, work experience and their familiarity with the industries investigated in the study. Of the 39 respondents, 34 provided age, education and work experience information. The respondents' ages ranged from 33 to 67; 38% were in their thirties, 45% were between 40 and 59 and 17% were in their sixties. About 24% of the sample held doctorates and the rest were evenly divided among Bachelors and Masters degree holders. Relevant work experience ranged between 6 and 40 years. Only 5% of the respondents had under 10 years' work experience. Of the remainder, about 35% had between 10 and 19 years' experience and the remainder had twenty years or more. Respondents' affiliations were with 35 different organizations that included private corporations, government laboratories and universities.

The respondent profile suggests that the sample, as a group, was highly qualified. Further, in the interests of meaningfulness, the results for each of the six industries studied are based only on the responses of individuals whose self-rated familiarity with the industry was 4 or more on a seven-point scale (1 = Not Familiar, 7 = Familiar). Although this reduced the sample size for many of the questions, the selectivity engenders greater confidence in the quality of the responses.

Given the nonprobability sample, the data are not amenable to statistical inference. The first stage survey results should therefore be interpreted qualitatively.

RESULTS

IMPORTANCE OF PERFORMANCE FACTORS

In Part A, respondents rated the relative importance of a set of fifteen performance factors on seven-point rating scales (1 = Not important, 7 = Very Important). The factors were rated separately for six industries: primary metals (ferrous and non-ferrous); fabricated metal (heat treatment), chemicals, glass, utility and incinerators. The fifteen performance factors related to the thermal and mechanical properties of the tubes as well as factors related to reliability, cost, handling and maintenance. The mean ratings are summarized below for each industry:

EXHIBIT 1: SUMMARY MEAN IMPORTANCE RATINGS OF PERFORMANCE FACTORS BY INDUSTRY

<u>Factor</u>	<u>INDUSTRY</u>					
	<u>PM</u>	<u>FM</u>	<u>CH</u>	<u>GL</u>	<u>UT</u>	<u>IN</u>
High Temperature Capability	6.2	5.4	5.2	6.8	5.5	5.8
High Thermal Effectiveness	5.4	5.3	5.4	5.4	5.8	5.1
High Thermal Conductivity	5.2	5.3	5.1	5.1	5.3	4.6
High Thermal Shock Resistance	6.0	5.7	5.6	6.0	5.6	5.6
High Pressure Capability	3.7	3.3	6.0	4.0	6.0	4.9
Corrosion Resistance	5.9	5.0	6.6	6.4	6.1	6.6
Low Leakage (through tubes)	5.3	5.2	6.2	5.3	5.8	5.3
Low Leakage (at joints)	5.2	5.3	6.1	5.3	5.8	5.2
Reliability	6.4	6.3	6.2	6.2	6.4	6.2
Durability (life)	6.0	6.3	6.1	6.2	6.4	6.2
Low Capital (installed) Cost	5.5	5.9	5.2	5.2	5.2	5.4
Low Tube Cost	5.2	5.5	4.6	5.0	4.9	5.0
Low Maintenance Cost	6.0	5.6	5.4	5.5	6.0	5.4
Ease of Joining	5.3	5.1	5.1	5.0	5.3	4.9
Ease of Handling/Installation	5.3	5.1	4.8	5.0	5.2	4.8

The detailed results of this section are presented in Tables 2-7. Taken together, the ratings suggest that the list of performance factors was complete and that the ratings show significant consensus. No performance factor outside the provided list was named consistently. None received a median importance rating of less than 3 (the lowest mean was 3.3) and the interquartile range exceeded two scale points in only two out of ninety cases. These indices suggest that the data obtained are reliable. We now discuss these detailed findings by industry.

Primary Metals (SIC CODE #3300)

Twenty three respondents indicated that they were familiar with this industry. As shown in Table 2, the median (and mean) rating was 5 or higher for all factors except high pressure capability which received a median rating of 4 (mean = 3.3). Reliability received a median importance rating of 7 (mean = 6.4) and durability was rated 6 (mean = 6.0). All thermal capability factors received median ratings of 6. However, of these, high temperature capability was most consistently viewed as important. Corrosion resistance and leakage through the tube also received median ratings of 6 and there was close to complete consensus on the importance of the former. Ease of joining and handling/installation ease were also rated important (mean ratings of 6). Interestingly, the ratings show that low maintenance cost (median rating of 6) was viewed as more important than either low capital cost or low tube cost (median ratings of 5). This is consistent with the high rated importance of reliability.

Fabricated Metals (SIC CODE #3400)

The twenty one respondents familiar with this industry had a pattern of ratings similar to primary metals (Table 3). As in the primary metals industry, reliability and durability had median importance ratings of 6 (both means = 3.3) with a tight interquartile range of 1. Pressure capability was least important (mean = 3.3, median = 3). The ratings of factors related to thermal capability were more variable. Among these, thermal shock resistance was rated as most important (mean = 5.7, median = 6) and high temperature capability was less critical than in primary metals. Leakage (at joints) and ease of joining were of concern (median = 6). In contrast to primary metals, low capital cost was most important of the cost factors (median = 6, mean = 5.9), though all cost factors were in the same importance range (median = 6) as in primary metals. The pattern of ratings for the other factors was also similar.

Chemicals (SIC CODE #2800):

Twenty-one respondents rated themselves as familiar with heat exchanger tube requirements in the chemical industry. Their importance rating pattern was different from those for the metals industries (Table 4). As expected, corrosion resistance (median = 7) was rated most important. Reliability and durability were also rated important (median = 6), but leakage rates (both through the tube and joints) were equally important. In contrast to the metals ratings, pressure capability received a consistent important rating of 6. Among thermal factors, thermal shock resistance was rated highest (median 6, mean 5.6). The tube cost was rated as least important (mean 4.6) and handling issues also did not seem to warrant as much attention (mean = 4.8).

Glass (SIC CODE #3200)

Twenty-two respondents claimed familiarity with heat exchanger tube requirements in the glass industry. Their ratings are summarized in Table 5. High temperature capability (mean = 6.8, median = 7.0, interquartile range = 0) and high thermal shock resistance were the critical factors as expected. As for chemicals, corrosion resistance was rated important (mean 6.4, median 7). Also, like in the other industries, reliability and durability were very important (medians = 6 and 7 respectively). Maintenance and capital costs (median = 6) were more important than tube cost (median = 5). The pressure capability factor (median = 4) was less important than in the chemical industry.

Utilities (SIC CODE 4900)

Twenty-nine respondents' data were analyzed for the utility industry (Table 6). Reliability and durability received the highest (median = 7) ratings. Corrosion resistance and pressure capability were also rated as very important (median = 6). Of cost factors, maintenance was the most important (mean = 6.0) and tube cost was the least important (mean = 4.9). Thermal effectiveness was rated as the most important thermal capability (mean = 5.8), although thermal conductivity and shock resistance also had identical median importance ratings of 6.

Incinerators (SIC CODE 4950)

Twenty-five respondents claimed familiarity with the requirements for heat-exchanger tubes for incinerators. Their responses (Table 7) show that as in the other industries, reliability and durability were rated consistently as among the most important factors (both medians = 6). Corrosion resistance, though, was most important (median = 7, mean = 6.6). Of the thermal factors, high temperature capability (mean = 5.8) and high thermal shock resistance (mean = 5.6) ranked next. Cost factors were rated as less important (means between 5.0 and 5.4), but consistent with some of the other industries, maintenance and capital costs were more important than tube costs. Pressure capability and handling factors were rated as less important.

Summary

These data show significant consensus among the respondents on the relative importance of the performance factors in each industry. Although most of the ratings were high, there were some sharp differences in how the factors rated in importance by industry. The following are the salient results from this section of the survey.

- * **High temperature capability** is important in all industries, most so in Glass.
- * **High thermal effectiveness** and **high thermal conductivity** are both perceived as important in most industries, but relatively less so than the other thermal capability factors.
- * **High thermal shock resistance** is consistently ranked among the top five important factors across all industries.
- * **High pressure capability** is relatively less important in the evaluation of heat exchanger tubes in the primary metal, fabricated metal, and glass and incinerator industries. It is among the more significant performance factors only in the chemical and utility industries. Otherwise it receives the lowest importance ratings.
- * Except in fabricated metals, **corrosion resistance** is rated as a very important factor. It receives the highest mean overall importance score in the chemical industry.
- * **Low leakage through the tube and joints** have collinear importance ratings. Both factors attain particular importance in the chemical and utility industries.
- * **Reliability and durability** are clearly the two most important factors across all the industries examined. This may reflect the fact that these two characteristics generally embody the end goal of all physical properties of heat exchanger tube material. Though one may interpret these ratings as implying that strength ratings (e.g., fracture toughness or Weibull modulus) are all important, it would be prudent to interpret these data qualitatively.
- * Among various cost factors, **low tube cost** is consistently rated among the less important factors. Although **low capital (installed) cost** is rated among the more important factors in fabricated metals, it is not viewed among the dominant factors across industries.
- * In contrast, **low maintenance cost**, a factor possibly correlated with reliability and durability, ranks consistently among the most important factors in the focal industries. This may reflect that the tubes may comprise a relatively uncontrollable and small portion of the overall expenditure associated with heat exchanger systems. Maintenance costs, on the other hand, are a recurring expense in need of monitoring and control.
- * Across the industries surveyed, **ease of joining** and **ease of handling and installation** were among the less significant performance factors. Each was considered important in

absolute terms. But the two factors typically tended to receive similar and lower ratings in the set. Since joining and handling problems are more critical for ceramic heat exchanger tubes, they may be less salient unless one deals with these materials.

Overall then, these data suggest that reliability and durability are key performance factors across all the industries surveyed. Of all cost factors, low maintenance cost (the result of higher reliability and durability) seems to receive high importance in our expert respondents' pooled judgments.

A few individuals rated the performance factors in other industries. In each case, the data are from one person and reflect idiosyncratic perceptions and preference. Table 8 tabulates these data. Also no other performance factors received mention with any consistency.

DESIRABLE PERFORMANCE SPECIFICATIONS

Part B of the survey focused on assessing a detailed set of performance specifications that are desirable in heat exchanger tubes in each of the six industries under study. The questions were keyed to the fifteen performance factors that were investigated in the previous section of the survey. For each of these factors, we worked with our technical consultants to identify (to the extent possible) the physical characteristic(s) that mapped most closely to the qualitative performance factor of interest. The respondents were then asked to provide estimates of the expected/desirable level (or range) of the physical characteristic for each of the industries under study.

Consistent with the performance factors rated, the questions pertained to the following issues:

- temperature capability range ($^{\circ}\text{F}$)
- thermal effectiveness range (%)
- thermal conductivity range ($\text{BTU/hr.in.}^{\circ}\text{F}$)
- temperature cycling or extent of thermal shock ($^{\circ}\text{F}$)
- pressure capability range (pounds per sq. in)
- type of corrosive materials in environment
- leakage rates through tubes and joints (%)
- mechanical properties related to reliability
 - strength (Kpsi)
 - fracture toughness ($\text{Kpsi} \cdot \text{in}^{1/2}$)
 - reliability (Weibull modulus)
- operating life
- capital (installed) cost
- operating cost
- payback period
- nature of joining
- desirable sizes (diameters and lengths) and shapes

We present a tabulation of the specifications profile for each of the industries studied.

EXHIBIT 2: SUMMARY OF DESIRABLE SPECIFICATIONS BY INDUSTRY (MEDIAN RESPONSES)
INDUSTRY

<u>Factors</u>	<u>PM</u>	<u>FM</u>	<u>CH</u>	<u>GL</u>	<u>UT</u>	<u>IN</u>
<u>Thermal factors:</u>						
Temperature Capability (°F)	1250-2500	500-1750	<500-2000	1000-2500	500-2000	500-2000
Thermal Effectiveness (%)	60-75	60-85	65-85	60-75	65-85	60-85
Thermal Conductivity (BTU/hr.in. ² °F)	.5-2	1-5	1-5	.5-5	1-5	1-5
Temperature Cycling (°F)	500-2500	<500-2000	<500-2000	500-2250	500-1750	<500-2250
<u>Mechanical Properties:</u>						
Pressure Capability (Psi)	<50	<50-50	<50-150	<50-50	<50-200	<50-50
Leakage Rate Thru Tubes (%)	.1-.5	<.1	<.1	.1-.5	<.1	<.1
Leakage Rate at Joints (%)	1-5	1-5	<1	1-5	<1	<1
Strength Rating (Kpsi)	20-35	20-35	35-50	20-35	20-35	20-35
Fracture Toughness (Kpsi.in ^{1/2})	5-10	10-15	10-15	10-15	15-20	15-20
Reliability (Weibull Modulus)	20-25	15-20	15-20	15-20	>25	20-25
<u>Other Factors:</u>						
Operating Life (Months)	24-36	24-36	>36	12-24	>36	24-36
Payback Period (Months)	18-24	18-24	24-30	18-24	30-36	18-24

Note: Desirable specifications for other factors are either qualitatively stated or unavailable. For further details please refer to the detailed tables.

The highly detailed probes may have stretched the limits of respondents' expertise. Though we encouraged answers to all questions, there was significant response attrition. However, this also ensured that the responses that we received were from those most involved in the issues addressed by the survey. Moreover, by using data only from respondents who passed the familiarity cutoff of 4, a plausible case may be made that the responses are meaningful.

Tables 9-21 provide detailed summaries of the responses. The number of responses on which the summaries are based is also indicated. These tables permit assessments of the specifications profile for each of the six industries. It is nevertheless instructive to conduct a comparative assessment of these specifications across the industries.

Thermal Capabilities

The **temperature capability range estimates** (Table 9) were most demanding for the primary metals and glass industries, with the median upper bound estimate being 2500°F. The median estimate for each of the remaining industries was 2000°F. The median lower bound estimates for primary metals and glass were 1250°F and 1000°F respectively whereas the other industry estimates were at 500°F or lower. These estimated ranges may need to be interpreted carefully as the data suggest that the respondents may have focused more on the upper end of temperature capability versus the full range in answering this question.

The median estimate (Table 10) of the lower bound of **thermal effectiveness** was between 60 and 65 percent for each industry surveyed. The median upper bound estimate was at 85% for all industries other than primary metals and glass where it was 75%. These two industries were also the least demanding in terms of **thermal conductivity**. The median lower bound estimate was 0.5 BTU/hr.in.°F whereas in the remaining industries it was 1.0 BTU/hr.in.°F. Also, the median upper bound estimate was 5.0 BTU/hr.in.°F for all industries other than primary metals where it was 2.0 BTU/hr.in.°F. See Table 11. Also, based on the median estimates in Table 12, the range of temperature cycling (**thermal shock**) that heat exchanger tubes must withstand is highest for primary metals and glass. In contrast, utilities have the least stringent demands on this criterion.

Pressure, Corrosion and Leakage

The chemical and utility industries were estimated to have the highest demands on **pressure capability**. The median estimates of the upper bound in these two industries were 150 and 200 psi respectively. The median lower bound estimate for all industries was <50 psi. These data are consistent with the performance factor importance ratings in Part A of the survey (Table 13).

Oxidation was the most commonly named (by at least 85%) cause of corrosion for heat-exchanger tubes in all industries. Flue gases were also named quite commonly (by at least 80%) in industries other than chemicals (by only 59%). A majority also named mineral acids as a problem in the primary metals, chemicals and incinerators. Slag was named by a significant

majority in all industries other than fabricated metals and chemicals. Not surprisingly, molten metal received majority mention in primary metals. (See Table 14).

Tolerance for **leakage through tubes and at joints** was lower than anticipated in most industries (Table 15). The median acceptable leakage through tubes for fabricated metals, chemicals, utilities and incinerator industries was < 0.1%, the lowest scale category. The estimates were a little higher in the remaining industries. Although acceptable leakage at joints was higher relative to leakage through the tubes, the median estimates were < 1% (i.e., also at the lowest category) for the chemical, utility and incinerator industries.

Reliability and Durability

Respondents were asked to estimate the normally acceptable **strength, fracture toughness and reliability** ratings for heat-exchanger tubes in various industries. The data are summarized in Table 16. The median acceptable strength estimate was 20-35 Kpsi for all industries except chemicals where it was 35-50 Kpsi. The median acceptable fracture toughness was estimated to be lowest for primary metals (5-10 $\text{Kpsi} \cdot \text{in}^{1/2}$). Fabricated metals, chemicals, and glass industries require 10-15 $\text{Kpsi} \cdot \text{in}^{1/2}$, the utilities and incinerator industries require 15-20 $\text{Kpsi} \cdot \text{in}^{1/2}$, whereas the primary metals industry requires 5-10 $\text{Kpsi} \cdot \text{in}^{1/2}$. Using the Weibull modulus values as the measure of reliability, the median was estimated at 15-20 in the fabricated metals, chemicals and glass industries, at 20-25 for the primary metals and incinerator industries and at >25 for the utilities industry.

However, care should be estimated in interpreting these figures. The nature of these strength measures may have stretched respondents' expertise. It is also unclear how the respondents map these technical specifications to field performance criteria such as the tube's life expectancy. Expected durability in this study was measured in terms of **operating life** of the heat exchanger tubes. The lowest estimated median life-expectancy of 12-24 months was in the glass industry. The median life-expectancy in the incinerators, primary and fabricated metals industries was 24-36 months, whereas it was the highest (>36 months) in the chemical and utility industries. See Table 17 for the detailed data.

Cost and Payback

Perhaps the least successful aspect of this study was the attempt to elicit specific cost estimates. Respondents could (did) not answer questions about the installed and operating costs of heat exchanger systems, making unit costs difficult to estimate. However, the response rate was significantly higher for the **payback period** question. The median response for the normally acceptable payback period was highest (30-36 months) in the utility industry, next highest (24-30

months) for the chemicals industry, whereas it was as low as 18-24 months in primary metals, fabricated metals, glass, and incinerator industries. These data indicate the cost-durability trade-offs in each of the industries and are consistent with the operating life data (Table 18).

Joining and Handling

Questions regarding **methods of joining** met with mixed responses. The respondents indicated the method of joining composite ceramic tubes to metal components used currently for heat exchanger applications in each type of industry. Mechanical joining methods were cited most commonly (by at least 64% in each industry). A majority in primary metals, fabricated metals and chemicals (50%, 50% and 69% respectively) also named thermal bonding. Although a number of other techniques were named in the survey (e.g., brazing) this was not attributable to specific industry experts (Table 19).

Shapes and Sizes

Finally, a set of questions asked respondents to indicate the commonly used shapes for heat-exchanger components and the commonly used sizes for heat exchanger tubes. Tubes were the most popular shape and were named by at least 80% across all industries. Fin plates were most commonly named for the chemical industry (61%) and they also received significant mention (>25%) in all other industries except glass (13%). Fin tubes also received a similar pattern of mentions, usage being most commonly noted in utilities (69%), chemicals (56%) and fabricated metals (53%). See Table 20 for detailed data on the frequency of mentions. This table also shows the frequencies of mention for various **inner diameters** and **lengths** of heat exchanger tubes.

Although the mentions varied by industry, inner diameters from 0.5 up to 6 inches and lengths between 3 and 20 feet were commonly noted for each industry. However, diameters greater than 10 inches and lengths greater than 20 feet were also noted by a number of the respondents. These data indicate the nature of tubes used in each industry. We discuss the implications of these data in the next section.

SCWRA TUBE VIS-A-VIS DESIRABLE SPECIFICATIONS

The implications of the above data are developed by comparing the anticipated capabilities of the silicon carbide whisker-reinforced alumina (SCWRA) tubes relative to the desirable specifications determined above in the focal industries. We also compare this

assessment to the qualitative summary assessments provided by respondents when asked to rate whether these performance factors would be key barriers or facilitators to adoption (Table 21).

Thermal Capabilities

The currently claimed temperature capability of SCWRA tubes is 2200°F. This upper bound is within the maximum temperature needed in most of the industries examined and covers a significant part of the range for even the primary metals and glass industries where the required capability is 2500°F. The anticipated thermal conductivity of SCWRA tubes is 1.69 BTU/hr.in.°F. at room temperature and 0.48 BTU/hr.in.°F at 2200°F. Although these numbers are within the (median) estimated range, they are at the lower end. Depending on the extent to which upper end requirements are critical, this could be a problem in some industries. In sharp contrast, the anticipated thermal shock resistance of SCWRA tubes is high. This capability of withstanding temperature cycling in excess of 1500°F is likely to be satisfactory for most industries.

Qualitative assessments of the impact of these performance factors on adoption are consistent with the above. As Table 21 shows, respondents rated the temperature capability and thermal shock resistance properties of SCWRA tubes among the key facilitators to adoption (median rating of 6 and 5 respectively). The respondents were more equivocal (median = 4) about the material's thermal conductivity properties, suggesting that this feature may need examination.

Pressure, Corrosion and Leakage

The anticipated pressure capability of the SCWRA tubes is expected to be comparable to or better than similar materials. As SCWRA tubes are expected to be resistant to all mineral acids, to most flue gases, to oxidation up to 2200°F, and to molten metals, corrosion resistance will be a significant facilitator to adoption in industries where the property is critical (e.g., chemicals and glass). Although SCWRA tubes should have acceptably low leakage rates of < 0.1% through the tubes, the leakage through the joints is somewhat greater than what respondents indicate as satisfactory.

The respondents' qualitative assessments generally corroborate the above. As expected, the material's corrosion resistance properties are seen as a key facilitator (median = 6). However, respondents expressed reservations about the pressure capability and leakage rates factors (median = 4).

Reliability and Durability

The anticipated strength of SCWRA tubes is higher than the acceptable median response ratings for all industries. The fracture toughness rating is however significantly lower than required in most industries. However, note that the anticipated fracture toughness rating of the SCWRA tubes is higher than that of most ceramic materials. Consequently, the results must be interpreted with caution. A similar caveat may apply for the reliability ratings (i.e., the Weibull modulus scores). The expected reliability, relative to other ceramic materials, is significantly better. Consistent with these assessments, the material's reliability and durability properties were viewed (see Table 21) as generally facilitating factors for adoption (median = 5).

The consistent emphasis on reliability and durability as important performance factors suggests that efforts to improve these performance features are critical for the future. The improved mechanical properties of SCWRA tubes were recognized by the respondents. However, they responded only with mild enthusiasm about the degree to which the current level will facilitate its adoption in new applications or in substitution or replacement of metals and other ceramics. This suggests a need for continued improvement.

Cost and Payback

Although a paucity of cost data does not permit a direct analysis of the economic attractiveness of the SCWRA tubes, it is not surprising that cost is a key barrier to adoption. Each of the cost factors received a median rating of 4 (see Table 21). Together with the other qualitative assessments, one anticipates that this rating reflects a significant reservation against the adoption of SCWRA tubes in mass applications. Rather, the data suggest that SCWRA tubes would be significantly more successful in selectively penetrating specific niche markets where the specialized application would strongly benefit from the material's advanced properties.

Thus, although the volume would be small, the markets would be well-protected from competitive inroads and would, most likely, support a fair price premium. The operating savings in heat exchanger applications is also directly related to fuel costs. More general penetration of these materials may be stimulated by a rise in fuel costs. Finally, from a life-cycle cost perspective, improved reliability and durability will lower maintenance costs and hence favorably influence cost comparisons against competing materials.

Joining and Handling

The joining and handling properties of the tubes were also not expected to facilitate adoption (Table 21). Each of these factors received a median rating of 4. Judging by the ratings, the respondents anticipated limited flexibility in terms of available joining technologies. They may

also have anticipated some constraints on the handling/installation of this ceramic material. Some qualitative comments received in response to a follow-up question reinforce this assessment. Respondents anticipated that available sizes may be somewhat restricted by the ceramic material's handling properties. Thus, customers may anticipate additional problems due to the need for joining smaller lengths of tubes. This would necessitate specific customer reassurances regarding the available solutions to the joining problems.

Summary

In summary, the comparison of the properties of the SCWRA tubes to the detailed specifications data show their strengths and weaknesses and how these may affect their adoption and general use in various industries. The findings are generally consistent with the respondents' ratings of these performance factors as facilitators or barriers to adoption. This consistency is additional evidence regarding the reliability and validity of the study results. The following are the salient conclusions from this analysis:

- * Respondents rated the temperature capability and thermal shock resistance properties of SCWRA tubes among the key facilitators to adoption. They were more equivocal about the material's thermal conductivity properties.
- * The material's corrosion resistance properties are seen as a key facilitator. However, respondents expressed reservations about the pressure capability and leakage rates factors.
- * Respondents recognize the improved reliability and durability of SCWRA tubes. However, they seem to demand continued improvements for significant adoption in new applications or in substitution or replacement of other ceramics and metals.
- * Although adoption of SCWRA tubes in mass applications is unlikely, they would be more successful in selectively penetrating specific niche markets. These niches would support small volumes but would be well-protected from competitive inroads and support a fair price premium.
- * More general penetration of these materials may be stimulated by a rise in fuel costs. Also, improved reliability and durability will lower maintenance costs and thereby favorably influence cost comparisons against competing materials.

SUBSTITUTION/REPLACEMENT OF HEAT-EXCHANGER TUBE MATERIAL

Part C of the survey focused on assessing respondents' perceptions and experiences with the current usage of metal, ceramic and composite materials for heat-exchanger tubes in the focal industries. Next, respondents received a thumbnail sketch of anticipated SCWRA tube specifications and a reference price and assessed replacement/substitution potential for the various materials at different price levels relative to this reference price. This was also done by focal industry. The findings are presented below.

Current Usage

Using a 5-point scale (1 = no usage and 5 = high usage), respondents reported that metal heat-exchanger tubes were the most popular in each focal industry. Usage was highest (median = 5) for fabricated metals, chemicals, and utilities and then for primary metals and incinerators (median = 4). Metal usage was rated lowest in the glass industry (median = 3). Ceramics use was highest in the glass industry (median = 3), moderate (median = 2) in primary and fabricated metals and chemicals and highly unusual (median = 1) in the utility and incinerator industries. Composites were used as being reported in moderate quantities (median = 2) only in the chemicals industry. No significant usage was reported in any other industry (median = 1). See Table 22 for details.

Replacement/Substitution Potential

Respondents indicated the likelihood of substitution of metals, ceramics and composites by SCWRA tubes using a 10-point scale (1 = very unlikely, 10 = very likely). An initial reference price of \$75-\$100 per linear foot was stated. The results (Table 23) show that SCWRA tubes were unlikely to substitute metals (median = 3), but the likelihood of substituting ceramic and composite material was quite high (medians = 7). Also, Table 24 shows that replacement/substitution potential was highest in the glass and incinerator industries (median = 5) followed by primary metals and chemicals (median = 4). The relatively low numbers probably reflect the generally low baseline usage rate of ceramic and composite materials.

Price Effects. Tables 23 and 24 also show price effects on replacement and substitution likelihoods. Respondents provided assessments of this substitution potential at prices 50% and 100% higher than the reference price above. Metal substitution was rated very unlikely at these prices (median = 1).

For ceramics, the median likelihood ratings dropped from 7 (at the reference price) to 4 and 3 at 50% and 100% higher prices respectively. For composites, the corresponding median likelihood ratings fell from 7 to 5 and 3 respectively. The data show that although market

penetration will be reduced significantly by an excessive price premium, there is a possibility that a moderate price premium may be sustainable against some materials in specific applications.

Respondents also estimated the likelihood that SCWRA tubes will eventually replace/substitute heat exchanger tubes currently used in the focal industries at price levels 50% and 100% higher than the reference price. At 50% higher prices, the glass and incinerator industries still showed some potential for replacement (median = 4). However, the replacement likelihood was very low if prices were to be 100% higher than the reference price.

Consistent with the previous analysis, these results show that a moderate price premium may be sustained against other ceramics and composite materials in specific industry applications. However, these niches would have to be carefully researched for needed specifications and the pricing tied to the specific operating and maintenance cost savings. Table 25 lists the current as well as the new industries and applications in which the respondents believed that SCWRA tubes would permit significant and new levels of heat recovery and additional applications.

In summary, the salient findings here are:

- * At the stated initial reference price (\$75-\$100 per linear foot), SCWRA tubes are unlikely to substitute metals, but the likelihood of substituting ceramic and composite material is quite high.
- * Replacement/substitution potential was highest in the glass and incinerator industries followed by primary metals and chemicals.
- * Although market penetration will be reduced significantly by an excessive price premium, a moderate price premium may be sustainable against some materials in specific applications.

MARKET SIZE AND GROWTH ESTIMATES

Part D, the final section of the survey, was designed to obtain estimates of the current market potential for SCWRA tubes and to estimate market growth patterns in the short, intermediate and long run. This quantitative estimation task was non trivial and many respondents were unable to provide meaningful data. We provide an analysis of the data that was obtained.

Market Size

Respondents encountered difficulty with estimating the current (1990) volume of heat exchanger tube material. Since this number was to serve as the baseline for all predictions, we could not develop estimates of the dollar or quantity volume of the market. Additional research was done to develop an alternative estimate of the 1990 volume from secondary data sources. The approach used to complete the numerical market size estimates is described later.

Market Breakdowns

Table 26 shows the estimated breakdowns of the 1990 dollar sales volume of heat exchanger tubes. The breakdown by material shows that 86.7% of the sales were estimated to be of metals, whereas ceramic and composite materials comprised 8.9% and 5.3% of sales respectively. The bulk of the volume was in the chemical, utility and metal (primary and fabricated) industries. Sales volumes were smallest in the glass and incinerator industries. Although the numbers have face validity, the means are based on a small number of responses and the estimates show significant variability. Hence the data must be viewed with caution.

Market Growth

Table 27 shows estimated sales growth rates in the short, intermediate and long run both with and without the introduction of SCWRA tubes in 1992. As the estimates show, the introduction of SCWRA tubes may provide a moderate boost to the sales growth rate presumably due to a broader range of applications. The respondents named specific applications and industries to pursue in this regard. The current (1990) growth rate (about 6%) is expected to reach around 9% by 1995 and then hold steady in the foreseeable future. As before the data are based on a small number of responses and should be interpreted with caution.

Table 28 shows the respondents' mean estimates of market share of each type of material at different points over the next 15 years. Starting with a 1.7% share in 1992 (introduction), SCWRA share is expected to rise to 5% by 1995, to 6% by 2000 and to 7.6% by 2005. This growth will be attained in a period where current ceramics and composite materials are expected to gain share steadily at the expense of metals.

Note that in their qualitative assessments, respondents had also stated that SCWRA tubes would primarily replace other ceramic and composite materials and would be unlikely to replace metals to any significant degree. Together, these data suggest that a two-stage replacement process may operate. Current ceramics and composite materials will steadily erode away the basic metal tube market. This first level substitution would be followed by a second level substitution whereby the current substitutes in turn would be replaced by SCWRA and other

higher performance composites. This scenario is consistent with substitution/replacement patterns in maturing industrial markets where application needs are met over time by increasingly improved material and equipment (Kotler 1991, Corey 1991).

Respondents also provided estimates of the market share of SCWRA tubes by industry. These estimates, from a smaller number of respondents, are somewhat lower than the aggregate estimates above. Although of lesser significance, these estimates provide another (more conservative) perspective on the market potential for SCWRA tubes.

Market Forecasts

We first developed an index estimate of the market size using the market growth data (both with and without the introduction of SCWRA tubes). The 1990 baseline total dollar sales of heat-exchanger tubes was set at 100. This index was then adjusted by the market proportion and growth rate estimates to develop the forecasts for this index. As shown in Table 29, the sales index is expected to grow to 121.4 in 1993 (the year after the anticipated introduction of the SCWRA tubes), to 144.4 by 1995, to 224.3 in the year 2000 and reach a level of 345.7 in 2005.

This index is also apportioned using the material-wise share data from Table 28. Thus, Table 29 includes a breakdown of the sales volume index by material (metal, ceramics, current composites and SCWRA) during the period between 1990 and 2005. Applying the respective market share estimates (5%, 6.6% and 7.6%), our projection tracks the SCWRA tubes sales index at 7.2, 14.8 and 26.3 in 1995, 2000 and 2005, respectively.

Estimates provided by Frost and Sullivan Reports (1990) in conjunction with projections made by Rebello (1987) suggest that the 1990 dollar sales volume of heat exchanger shell and tube materials was \$821 million. As shown in Table 30, the most likely estimate of 1990 tube sales was taken to be 50% of this volume. Table 30 then shows the complete market forecast developed from these data.

As the most likely estimates show, the base total market for tubes was \$410 million in 1990. This is expected to grow to \$582 million in 1995, \$867 million in 2000 and \$1251 million in 2005. The introduction of SCWRA tubes is expected to accelerate the growth to corresponding volumes of \$593 million, \$921 million and \$1419 million, respectively. Of this volume, metals, (currently 87% share) were expected to drop progressively to 81%, 75% and 69% respectively. Ceramics and composites were expected to post corresponding gains. Specifically, the estimated market share of SCWRA tubes is 5.0%, 6.6% and 7.6%, translating to most likely estimated sales volumes of \$30 million, \$61 million and \$108 million in 1995, 2000 and 2005, respectively.

CONCLUSIONS

SUMMARY OF FINDINGS

These first stage results provide an encouraging picture of the market potential for SCWRA tubes and suggest directions for future technical and development work. The key results may be summarized as follows:

- * There is a small, but growing market for SCWRA tubes in heat exchanger applications. The tubes' temperature capability, thermal shock resistance and corrosion resistance properties are expected to facilitate adoption.
- * Although the improved reliability and durability of SCWRA tubes is recognized, more work is needed on further improving these features. With such improvements, one may accelerate adoption for new applications or substantial replacement and substitution.
- * Other disadvantages in the areas of thermal conductivity, pressure capability and leakage rates, along with potential customer concerns regarding joining and handling issues, must also be addressed.
- * The anticipated cost/specifications of SCWRA make it appropriate for niche applications. In some cases, their improved properties will permit previously infeasible recovery levels. In other cases, as ceramics and other composites make inroads into applications where metals are currently popular, SCWRA tubes will follow as a second level substitute for current ceramics and composites.
- * Although volume and overall market share is expected to be small, SCWRA tubes should be able to sustain a moderate price premium in these high performance applications.
- * Improved reliability and durability should lower maintenance costs and favorably influence life-cycle cost comparisons with other competing materials. This should further facilitate adoption.

FUTURE RESEARCH

The results reported here are from the first stage of the Delphi study. When a decision is made to proceed to the second phase, a tabulated summary of the first stage results will be returned to the respondents along with a cover letter and an accompanying questionnaire for the second stage. The responses to this second stage survey will give us the final refined estimates from the Delphi study. This will provide a more complete assessment of the product technology and market potential for SCWRA heat-exchanger tubes.

REFERENCES

- S. Richlen, (1985). "A Survey of Ceramic Heat Exchanger Opportunities," pp. 3-14 in Advances in Ceramics, Vol. 14, Ceramic in Heat Exchanger. Edited by B. D. Foster and J. D. Patton, the American Ceramic Society, Inc., Columbus, OH.
- Mueller Associates, Inc. (1987). Assessment of High Pressure Heat Exchange Systems Technology, Vol. 1, Technology Assessment and Research and Development Needs, DOE/CE/40716-2 (Vol 1), DOE, Washington, DC.
- B. D. Foster and J. B. Patton, (1985). Advances in Ceramics, Vol. 14, Ceramics in Heat Exchangers, The American Ceramic Society, Inc. Columbus, OH.
- T. N. Tiegs and P. F. Becher, (1987), "Sintered Al_2O_3 -SiC Composites," Bull. Am. Ceram. Soc. 66(2), 339-42.
- M. J. Janney, E. S. Bomar, and M. C. Vance, (1989). Extrusion of Alumina-Silicon Carbide Whisker Composites, ORNL TM 10373.
- D. A. Kudon and M. R. Frankel, (1989). "Going to the Oracle for Strategic Planning: The Delphi Process, Handbook of Business Strategy 1988/1989 Yearbook, Warren, Gorham & Lamont, Boston, New York.
- R. P. Larsen and A. D. Vyas, (1988), "The Outlook for Ceramics in Heat Engines, 1990-2010: Results of a Worldwide Delphi Survey, SAE Technical Paper Series, International Congress and Exposition, Detroit, Michigan, February 29-March 4.
- Frost and Sullivan Reports (1990. Market for Heat Exchangers A2146, Frost and Sullivan Inc., 106 Fulton Street, New York, N.Y. 10038-2786.
- Wilfred J. Rebello, (1987). Assessment of Heat Transfer Enhancement and Fouling in Industrial Heat Exchangers, Contract #AC01-84CE40716, U.S. Department of Energy, Office of Industrial Programs, Washington, D.C.

TABLE 1**PROFILE OF RESPONDENTS**

<u>Resp.</u>	<u>Age</u>	<u>Education</u>	<u>W. Exp</u>	<u>Industry Familiarity</u>
1	33	MBA	10	UT
2	56	MS	35	None
3	63	BS ME	40	PM, FM, CH, G, UT, IN, B
4	34	PhD	6	CH, IN
5	55	PhD	34	UT, DESALINATION
6	54	BS ChE	32	FM, CH, G, IN
7	36	M.Engg	13	CH, UT, IN
8	42	BS	22	PM, FM, CH, G, UT, IN
9	37	BS ME	16	PM, FM, CH, G, UT, IN
10	67	MS	40	PM, FM, CH, UT, IN
11	59	MS	28	PM, FM, G, UT, IN
12	36	BA, BS	13	PM, FM, CH, G, UT, IN, CC
13	65	MS	40	PM, FM, CH, G, UT, IN
14	57	MS	33	PM, FM, CH, UT, IN
15	55	BSIE	30	FM, CH, G
16	49	PhD	22	PM, G, UT, IN
17	36	BS	14	AIR CONDITIONING
18	60	PhD	35	PM, FM, G
19	53	BS	30	PM, CH, G, UT, IN
20	50	BS	25	CH, PHARMACEUTICALS
21	40	ChED	16	CH, UT, IN, REFINING
22	34	MS	6	PM, FM, UT, IN
23	55	BSME	26	UT, IN
24	55	BS	34	PM, UT, IN
25	38	BS	10	G, UT, IN
26	60	MS	28	PM, FM, G, UT, IN
27	39	MBA	17	PM, FM, CH, UT, IN
28	32	MS, MBA	17	PM, FM, CH, G, UT, IN
29	32	M.Chem	10	PM, CH, G, UT, IN
30	47	NA	25	FM, CH, G, UT, IN, FURN.
31	35	BSME	14	FM, UT
32	35	PhD	10	PM, FM, G, UT
33	60	PhD	36	PM, FM, CH, G, UT
34	55	PhD	35	PM, FM, CH, G, UT, IN, PET.
35	Not Available			PM, FM, CH, G, UT, IN
36	Not Available			PM, FM, CH, G, UT, IN
37	Not Available			PM, CH, UT, IN
38	Not Available			G, UT
39	Not Available			AEROSPACE

Abbreviation:

PM = Primary Metals
 CH = Chemicals
 UT = Utility
 B = Burner
 FURN = Furnaces

FM = Fabricated Metals
 G = Glass
 IN = Incinerator
 CC = Cement Calciner
 PET = Petroleum

TABLE 2**IMPORTANCE OF PERFORMANCE FACTORS FOR HEAT EXCHANGER TUBES****PRIMARY METALS (FERROUS AND NON-FERROUS) INDUSTRY****SIC CODE # 3300**

	Number of Responses	Mean	First Quartile	Median	Third Quartile
High Temperature Capability	23	6.2	6	6	7
High Thermal Effectiveness	23	5.4	4	6	7
High Thermal Conductivity	23	5.2	4	6	6
High Thermal Shock Resistance	23	6.0	5	6	7
High Pressure Capability	23	3.7	3	4	5
Corrosion Resistance	23	5.9	6	6	6
Low Leakage (through tube)	23	5.3	4	6	6
Low Leakage (at joints)	23	5.2	4	5	7
Reliability	23	6.4	6	7	7
Durability (Life)	23	6.0	5	6	7
Low Capital (installed) Cost	23	5.5	4	5	7
Low Tube Cost	23	5.2	4	5	6
Low Maintenance Cost	23	6.0	6	6	7
Ease of joining	23	5.3	4	6	6
Ease of handling/installation	23	5.3	4	6	6
Other factors (Please indicate):		None consistently named			

Ratings: 1 = Not Important
7 = Very Important

TABLE 3**IMPORTANCE OF PERFORMANCE FACTORS FOR HEAT EXCHANGER TUBES****FABRICATED METAL (HEAT-TREATING) INDUSTRY**
SIC CODE # 3400

	Number of Responses	Mean	First Quartile	Median	Third Quartile
High Temperature Capability	21	5.4	5	5	6
High Thermal Effectiveness	21	5.3	4	6	6
High Thermal Conductivity	21	5.3	4	5	7
High Thermal Shock Resistance	22	5.7	5	6	7
High Pressure Capability	21	3.3	2	3	5
Corrosion Resistance	21	5.0	4	5	6
Low Leakage (through tube)	21	5.2	4	5	7
Low Leakage (at joints)	21	5.3	5	6	6
Reliability	21	6.3	6	6	7
Durability (Life)	21	6.3	6	6	7
Low Capital (installed) Cost	21	5.9	5	6	7
Low Tube Cost	21	5.5	5	6	6
Low Maintenance Cost	21	5.6	5	6	6
Ease of joining	21	5.1	4	6	6
Ease of handling/installation	19	5.1	4	5	6
Other factors (Please indicate):		None consistently named			

Ratings: 1 = Not Important
7 = Very Important

TABLE 4**IMPORTANCE OF PERFORMANCE FACTORS FOR HEAT EXCHANGER TUBES****CHEMICAL INDUSTRY**
SIC CODE # 2800

	Number of Responses	Mean	First Quartile	Median	Third Quartile
High Temperature Capability	21	5.2	4	5	6
High Thermal Effectiveness	21	5.4	5	6	6
High Thermal Conductivity	21	5.1	4	5	6
High Thermal Shock Resistance	21	5.6	5	6	6
High Pressure Capability	20	6.0	6	6	6
Corrosion Resistance	21	6.6	6	7	7
Low Leakage (through tube)	21	6.2	6	6	7
Low Leakage (at joints)	21	6.1	6	6	7
Reliability	21	6.2	6	6	7
Durability (Life)	21	6.1	6	6	7
Low Capital (installed) Cost	21	5.2	5	5	6
Low Tube Cost	21	4.6	4	5	5
Low Maintenance Cost	21	5.4	5	6	6
Ease of joining	21	5.1	5	5	6
Ease of handling/installation	21	4.8	4	5	6
Other factors (Please indicate):		None consistently named			

Ratings: 1 = Not Important
7 = Very Important

TABLE 5**IMPORTANCE OF PERFORMANCE FACTORS FOR HEAT EXCHANGER TUBES****GLASS INDUSTRY**
SIC CODE # 3200

	Number of Responses	Mean	First Quartile	Median	Third Quartile
High Temperature Capability	21	6.8	7	7	7
High Thermal Effectiveness	22	5.4	5	5	7
High Thermal Conductivity	22	5.1	5	5	7
High Thermal Shock Resistance	22	6.0	6	6	7
High Pressure Capability	22	4.0	3	4	5
Corrosion Resistance	22	6.4	6	7	7
Low Leakage (through tube)	22	5.3	5	6	6
Low Leakage (at joints)	22	5.3	5	6	6
Reliability	22	6.2	6	6	7
Durability (Life)	22	6.4	6	7	7
Low Capital (installed) Cost	22	5.2	5	6	7
Low Tube Cost	22	5.0	4	5	6
Low Maintenance Cost	22	5.5	5	6	6
Ease of joining	22	5.0	4	5	6
Ease of handling/installation	21	5.0	4	5	6
Other factors (Please indicate):		None consistently named			

Ratings: 1 = Not Important
7 = Very Important

TABLE 6**IMPORTANCE OF PERFORMANCE FACTORS FOR HEAT EXCHANGER TUBES****UTILITY INDUSTRY**
SIC CODE # 4900

	Number of Responses	Mean	First Quartile	Median	Third Quartile
High Temperature Capability	29	5.5	5	5	7
High Thermal Effectiveness	29	5.8	6	6	7
High Thermal Conductivity	29	5.3	4	6	7
High Thermal Shock Resistance	29	5.6	5	6	7
High Pressure Capability	29	6.0	5	6	7
Corrosion Resistance	29	6.1	6	6	7
Low Leakage (through tube)	29	5.8	5	6	7
Low Leakage (at joints)	29	5.8	5	6	6
Reliability	29	6.4	6	7	7
Durability (Life)	29	6.4	6	7	7
Low Capital (installed) Cost	29	5.2	5	6	7
Low Tube Cost	29	4.9	4	5	6
Low Maintenance Cost	29	6.0	5	6	7
Ease of joining	29	5.3	4	6	6
Ease of handling/installation	29	5.2	4	5	6
Other factors (Please indicate):		None consistently named			

Ratings: 1 = Not Important
7 = Very Important

TABLE 7**IMPORTANCE OF PERFORMANCE FACTORS FOR HEAT EXCHANGER TUBES****INCINERATOR INDUSTRY****SIC CODE # 4950**

	Number of Responses	Mean	First Quartile	Median	Third Quartile
High Temperature Capability	25	5.8	5	6	7
High Thermal Effectiveness	25	5.1	4	5	6
High Thermal Conductivity	25	4.6	4	5	6
High Thermal Shock Resistance	25	5.6	5	6	7
High Pressure Capability	25	4.9	4	5	6
Corrosion Resistance	25	6.6	6	7	7
Low Leakage (through tube)	25	5.3	4	6	6
Low Leakage (at joints)	25	5.2	4	6	6
Reliability	25	6.2	6	6	7
Durability (Life)	25	6.1	6	6	7
Low Capital (installed) Cost	25	5.4	5	5	6
Low Tube Cost	25	5.0	4	5	6
Low Maintenance Cost	25	5.4	5	6	7
Ease of joining	25	4.9	4	5	6
Ease of handling/installation	25	4.8	4	5	6
Other factors (Please indicate):		None consistently named			

Ratings: 1 = Not Important

7 = Very Important

TABLE 8**PERFORMANCE DATA FOR OTHER INDUSTRIES**

	<u>AC/ REF</u>	<u>AS</u>	<u>CC</u>	<u>DS</u>	<u>IG/ OB</u>	<u>PROC FURN</u>	<u>PHAR</u>
High Temperature Capability	1	3	4	2	7	3	3
High Thermal Effectiveness	6	5	1	7	6	5	5
High Thermal Conductivity	6	5	1	6	6	5	5
High Thermal Shock Resistance	2	4	1	4	7	4	4
High Pressure Capability	5	3	4	2	4	3	3
Corrosion Resistance	4	6	6	7	6	6	6
Low Leakage (through tube)	7	7	4	7	6	7	7
Low Leakage (at joints)	6	7	4	7	6	7	7
Reliability	6	7	7	7	6	7	7
Durability (life)	6	5	7	7	6	5	5
Low Capital (installed) Cost	6	4	5	7	5	4	4
Low Tube Cost	6	4	5	7	5	4	4
Low Maintenance Cost	3	3	3	7	6	3	3
Ease of Joining	6	5	4	5	5	5	5
Ease of Handling/Installation	5	5	4	5	5	5	5
Other factors (Please Indicate)	None Consistently Named						

Ratings 1 = Not Important
7 = Very Important

Notes:

- AS = Aerospace
 AC/REF = Air-Conditioning and Refrigeration
 CC = Cement Calciners
 DS = Desalination
 IG/OB = Industrial Gas and Oil Burners
 PROC FUR = Processing Furnace
 PHAR = Pharmaceuticals

- Ratings are from single respondents

TABLE 9**DESIRABLE PERFORMANCE SPECIFICATION FOR HEAT EXCHANGER TUBES****FACTOR: TEMPERATURE CAPABILITY (DEGREES FAHRENHEIT)****INDUSTRY****TEMPERATURE RANGE (DEGREES FARENHEIT)**

	Number of Resps.	LOWER BOUND			UPPER BOUND		
		First <u>Quartile</u>	Median	Third <u>Quartile</u>	First <u>Quartile</u>	Median	Third <u>Quartile</u>
Primary Metals	21	500	1250	1500	2250	2500	>2500
Fabricated Metals	20	<500	500	1250	1750	2000	2250
Chemicals	20	<500	<500	1000	2000	2000	2500
Glass	19	500	1000	1750	2250	2500	>2500
Utilities	27	<500	500	1000	1250	2000	2500
Incinerators	24	<500	500	1500	1750	2000	2250

TABLE 10**DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBES****FACTOR: THERMAL EFFECTIVENESS**
(PERCENTAGE)**INDUSTRY****THERMAL EFFECTIVENESS (PERCENTAGE)**

	Number of Resps.	LOWER BOUND			UPPER BOUND		
		<u>First Quartile</u>	Median	<u>Third Quartile</u>	<u>First Quartile</u>	Median	<u>Third Quartile</u>
Primary Metals	12	60	60	65	70	75	85
Fabricated Metals	12	60	60	65	75	85	90
Chemicals	14	60	65	80	80	85	95
Glass	12	60	60	60	70	75	85
Utilities	14	60	65	85	80	85	95
Incinerators	12	60	60	70	70	85	95

TABLE 11**DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBES****FACTOR: THERMAL CONDUCTIVITY**

<u>INDUSTRY</u>	<u>THERMAL CONDUCTIVITY (BTU/hr.in. °F)</u>						
	Number of Resps.	LOWER BOUND			UPPER BOUND		
		<u>First Quartile</u>	<u>Median</u>	<u>Third Quartile</u>	<u>First Quartile</u>	<u>Median</u>	<u>Third Quartile</u>
Primary Metals	13	0.25	0.5	1.0	2.0	2.0	5.0
Fabricated Metals	13	0.5	1.0	1.0	2.0	5.0	10.0
Chemicals	12	0.5	1.0	2.0	2.0	5.0	>10.0
Glass	10	0.5	0.5	1.0	2.0	5.0	5.0
Utilities	16	0.5	1.0	2.0	2.0	5.0	>10.0
Incinerators	12	0.5	1.0	1.0	2.0	5.0	5.0

TABLE 12**DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBES****FACTOR: TEMPERATURE CYCLING (THERMAL SHOCK)****INDUSTRY****TEMPERATURE RANGE (DEGREES FARENHEIT)**

	Number of Resps.	LOWER BOUND			UPPER BOUND		
		<u>First Quartile</u>	<u>Median</u>	<u>Third Quartile</u>	<u>First Quartile</u>	<u>Median</u>	<u>Third Quartile</u>
Primary Metals	19	<500	500	1000	2000	2500	2500
Fabricated Metals	17	<500	<500	500	1500	2000	2250
Chemicals	18	<500	<500	500	1000	2000	2500
Glass	18	<500	500	1250	1750	2250	>2500
Utilities	24	<500	500	1000	1250	1750	2250
Incinerators	20	<500	<500	500	1500	2000	2250

TABLE 13**DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBES****FACTOR: PRESSURE CAPABILITY (POUNDS PER SQUARE INCH)****INDUSTRY****PRESSURE CAPABILITY RANGE (Pounds per sq. inch)**

	Number of Resps.	LOWER BOUND			UPPER BOUND		
		First <u>Quartile</u>	Median	Third <u>Quartile</u>	First <u>Quartile</u>	Median	Third <u>Quartile</u>
Primary Metals	15	<50	<50	50	<50	<50	100
Fabricated Metals	13	<50	<50	<50	<50	50	100
Chemicals	16	<50	<50	<50	150	150	>200
Glass	13	<50	<50	<50	<50	50	150
Utilities	22	<50	<50	<50	200	200	>200
Incinerators	16	<50	<50	<50	<50	50	200

TABLE 14**DESIRABLE PERFORMANCE SPECIFICATION FOR HEAT EXCHANGER TUBES****FACTOR: CORROSION RESISTANCE**

<u>INDUSTRY</u>	<u>% NAMING CORROSIVE MATERIAL</u>						
	Number of Resps.	Mineral Acids	Flue Gases	Slag	Oxida- tion	Molten Metals	Other
Primary Metals	21	62	95	71	91	62	5
Fabricated Metals	20	25	95	25	95	15	5
Chemicals	22	64	59	4	86	13	9
Glass	20	35	85	60	85	10	0
Utilities	25	44	80	60	92	8	0
Incinerators	23	65	91	61	82	40	4

Other corrosive materials mentioned are:

- * Molten Glass
- * Molten Salts, Sulphates
- * Hydrogen
- * Carburization
- * Alkali and Salt Fluxes
- * Petroleum
- * Chlorides

TABLE 15**DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBES****FACTOR: LEAKAGE RATE****A. LEAKAGE RATE THROUGH TUBES (PERCENT)**

<u>INDUSTRY</u>	<u>LEAKAGE RATE (PERCENT)</u>			
	Number of Resps.	First Quartile	Median	Third Quartile
Primary Metals	16	<.1	0.1-0.5	0.5-1.0
Fabricated Metals	15	<.1	<.1	0.5-1.0
Chemicals	17	<.1	<.1	0.1-0.5
Glass	13	<.1	0.1-0.5	0.5-1.0
Utilities	20	<.1	<.1	0.5-1.0
Incinerators	15	<.1	<.1	0.5-1.0

B. LEAKAGE RATE AT JOINTS (PERCENT)

<u>INDUSTRY</u>	<u>LEAKAGE RATE (PERCENT)</u>			
	Number of Resps.	First Quartile	Median	Third Quartile
Primary Metals	16	<1	1-5	1-5
Fabricated Metals	15	<1	1-5	1-5
Chemicals	17	<1	<1	<1
Glass	14	<1	1-5	5-10
Utilities	21	<1	<1	1-5
Incinerators	17	<1	<1	1-5

TABLE 16**DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBES****FACTOR: MECHANICAL PROPERTIES****A. Strength rating**

<u>INDUSTRY</u>		<u>Kilo-Pounds/sq. in. (Kpsi)</u>		
	<u>Number of Resps.</u>	<u>First Quartile</u>	<u>Median</u>	<u>Third Quartile</u>
Primary Metals	12	20-35	20-35	35-50
Fabricated Metals	11	20-35	20-35	50-65
Chemicals	9	20-35	35-50	50-65
Glass	11	20-35	20-35	35-50
Utilities	15	20-35	20-35	50-65
Incinerators	11	20-35	20-35	35-50

B. Fracture toughness rating

<u>INDUSTRY</u>		<u>Kpsi · in^{1/2}</u>		
	<u>Number of Resps</u>	<u>First Quartile</u>	<u>Median</u>	<u>Third Quartile</u>
Primary Metals	11	2-5	5-10	10-15
Fabricated Metals	12	2-5	10-15	10-15
Chemicals	10	5-10	10-15	>20
Glass	13	2-5	10-15	15-20
Utilities	14	5-10	15-20	>20
Incinerators	11	2-5	15-20	>20

C. Reliability rating

<u>INDUSTRY</u>		<u>Weibull Modulus</u>		
	<u>Number of Resps.</u>	<u>First Quartile</u>	<u>Median</u>	<u>Third Quartile</u>
Primary Metals	9	15-20	20-25	20-25
Fabricated Metals	10	15-20	15-20	20-25
Chemicals	9	15-20	15-20	>25
Glass	12	15-20	15-20	20-25
Utilities	13	15-20	>25	>25
Incinerators	12	15-20	20-25	>25

TABLE 17
DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBES
FACTOR: OPERATING LIFE IN MONTHS

<u>INDUSTRY</u>	<u>LIFETIME IN MONTHS</u>			
	Number of Resps.	<u>First Quartile</u>	Median	<u>Third Quartile</u>
Primary Metals	17	12-24	24-36	>36
Fabricated Metals	15	12-24	24-36	>36
Chemicals	17	24-36	>36	>36
Glass	17	6-12	12-24	>36
Utilities	25	24-36	>36	>36
Incinerators	18	12-24	24-36	>36

TABLE 18DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBESFACTOR: PAYBACK PERIODS IN MONTHS

<u>INDUSTRY</u>		<u>MONTHS</u>		
	Number of Resps.	<u>First Quartile</u>	Median	<u>Third Quartile</u>
Primary Metals	18	12-18	18-24	30-36
Fabricated Metals	14	12-18	18-24	24-30
Chemicals	16	12-18	24-30	30-36
Glass	16	12-18	18-24	30-36
Utilities	20	18-24	30-36	> 36
Incinerators	16	18-24	18-24	30-36

TABLE 19**DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGER TUBES****FACTOR: JOINING METHODS****TYPE OF JOINING****INDUSTRY****% NAMING JOINING METHOD**

	<u>Mechanical</u>	<u>Thermal Bonding</u>	<u>Other</u>	<u>Number of Resps.</u>
Primary Metals	64	50	0	14
Fabricated Metals	92	50	0	12
Chemicals	69	69	0	13
Glass	79	35	0	14
Utilities	80	40	0	15
Incinerators	91	27	0	11

Other types of joining mentioned are:

- * Brazing
- * O-King Seals

TABLE 20**DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT EXCHANGERS****FACTOR: SIZES****A: SHAPES****INDUSTRY****% NAMING SHAPE**

	<u>TUBES</u>	<u>FIN PLATES</u>	<u>FIN TUBES</u>	<u>Number of Resps.</u>
Primary Metals	81	37	31	16
Fabricated Metals	93	47	53	15
Chemicals	88	61	56	18
Glass	93	13	13	15
Utilities	91	41	69	22
Incinerators	94	25	44	16

B: TUBES INNER DIAMETER (INCHES)**INDUSTRY****% NAMING INNER DIAMETER (INCHES)**

	<u>0.5-1</u>	<u>1-2</u>	<u>2-4</u>	<u>4-6</u>	<u>6-10</u>	<u>>10</u>	<u>Number of Resps.</u>
Primary Metals	20	33	47	60	13	13	15
Fabricated Metals	45	73	45	27	14	7	22
Chemicals	21	71	57	57	14	7	14
Glass	33	27	53	33	13	13	15
Utilities	33	20	60	60	7	7	15
Incinerators	56	38	56	13	13	13	16

C. TUBES LENGTHS (FEET)**INDUSTRY****% NAMING LENGTHS (FEET)**

	<u><1</u>	<u>1-3</u>	<u>3-6</u>	<u>6-10</u>	<u>10-20</u>	<u>>20</u>	<u>Number of Resps.</u>
Primary Metals	0	12	59	76	18	12	17
Fabricated Metals	13	18	63	56	31	13	16
Chemicals	6	35	53	59	47	53	17
Glass	6	13	38	75	25	25	16
Utilities	0	4	30	57	61	65	23
Incinerators	6	22	39	67	33	44	18

TABLE 21**FACILITATORS AND BARRIERS FOR INTRODUCING SCWRA TUBES**

PERFORMANCE FACTOR	Number of Resps.	Mean	First Quartile	Median	Third Quartile
Temperature Capability	31	5.6	4	6	7
Thermal Effectiveness	31	4.8	3	5	6
Thermal Conductivity	31	4.1	3	4	5
Thermal Shock	30	4.4	3	5	6
Pressure Capability	28	4.1	3	4	5
Corrosion Resistance	32	5.9	5	6	7
Leakage (through tube)	31	4.4	3	4	6
Leakage (at joints)	31	3.9	3	4	5
Reliability	31	4.7	3	5	6
Durability (life)	31	5.1	4	5	7
Capital (installed) Cost	32	3.8	2	4	5
Tube Cost	33	3.5	2	4	5
Maintenance Cost	30	4.3	3	4	5
Ease/difficulty of joining	31	3.9	3	4	5
Ease/difficulty of handling/installation	28	3.8	3	4	4
Other factors		None consistently mentioned			

Ratings: 1 = Key Barrier
7 = Key Facilitator

TABLE 22**USAGE OF DIFFERENT HEAT EXCHANGER MATERIALS****A: Primary Metals**

	Number of Resps.	Mean	First Quartile	Median	Third Quartile
Metal	19	3.9	3	4	5
Ceramics	19	2.3	2	2	3
Composites	18	1.8	1	1	2

B: Fabricated Metals

	Number of Resps.	Mean	First Quartile	Median	Third Quartile
Metal	18	4.4	4	5	5
Ceramics	18	2.2	1	2	3
Composites	16	1.6	1	1	2

C: Chemicals

	Number of Resps.	Mean	First Quartile	Median	Third Quartile
Metal	20	4.4	4	5	5
Ceramics	20	2.2	2	2	2
Composites	18	1.9	1	2	3

D: Glass

	Number of Resps.	Mean	First Quartile	Median	Third Quartile
Metal	19	3.5	2	3	5
Ceramics	19	3.2	2	3	5
Composites	17	1.6	1	1	2

E: Utilities

	Number of Resps.	Mean	First Quartile	Median	Third Quartile
Metal	25	4.4	4	5	5
Ceramics	24	1.4	1	1	1
Composites	23	1.5	1	1	1

F: Incinerators

	Number of Resps.	Mean	First Quartile	Median	Third Quartile
Metal	22	4.1	3	4	5
Ceramics	21	1.5	1	1	2
Composites	20	1.3	1	1	1

Ratings: 1 = No usage
5 = High Usage

TABLE 23**SCWRA AGAINST EXISTING HEAT EXCHANGER MATERIALS****LIKELIHOOD OF SUBSTITUTION****A: At the reference price (\$75-\$100 per linear foot)**

MATERIAL	Number of Resps.	Mean	First <u>Quartile</u>	Median	Third <u>Quartile</u>
Metal	35	3.8	2	3	6
Ceramics	33	6.5	5	7	8
Composites	28	6.3	4	7	8

B: 50% higher than the reference price

MATERIAL	Number of Resps.	Mean	First <u>Quartile</u>	Median	Third <u>Quartile</u>
Metal	33	2.8	1	1	4
Ceramics	30	4.2	2	4	6
Composites	25	4.4	2	5	6

C: 100% higher than the reference price

MATERIAL	Number of Resps.	Mean	First <u>Quartile</u>	Median	Third <u>Quartile</u>
Metal	33	2.2	1	1	2
Ceramics	30	3.2	1	3	5
Composites	25	3.5	1	3	5

Ratings: 1 = Very unlikely
10 = Very Likely

TABLE 24**SCWRA AGAINST EXISTING HEAT EXCHANGER TUBES****LIKELIHOOD OF SUBSTITUTION (BY INDUSTRY)****A: At the reference price (\$75-\$125 per linear foot)**

INDUSTRY	Number of Resps.	Mean	First <u>Quartile</u>	Median	Third <u>Quartile</u>
Primary Metals	15	4.6	2	4	7
Fabricated Metals	15	3.8	2	3	6
Chemicals	17	4.6	3	4	6
Glass	17	5.2	3	5	8
Utility	22	3.5	2	2	5
Incinerators	19	4.6	3	5	6
Other					

B: 50% higher than the reference price

INDUSTRY	Number of Resps.	Mean	First <u>Quartile</u>	Median	Third <u>Quartile</u>
Primary Metals	15	3.2	1	2	5
Fabricated Metals	15	2.3	1	2	3
Chemicals	17	3.8	2	3	5
Glass	19	4.3	2	4	6
Utility	22	2.9	1	2	4
Incinerators	18	3.7	2	4	5

C: 100% higher than the reference price

INDUSTRY	Number of Resps.	Mean	First <u>Quartile</u>	Median	Third <u>Quartile</u>
Primary Metals	15	2.4	1	1	3
Fabricated Metals	15	1.8	1	1	2
Chemicals	17	2.9	1	2	3
Glass	19	2.9	1	2	4
Utility	22	2.3	1	1	2
Incinerators	19	2.6	1	1	3

Ratings: 1 = Very Unlikely
10 = Very Likely

TABLE 25**INDUSTRIES/APPLICATION OF SCWRA HEAT-EXCHANGER TUBES****CURRENT INDUSTRIES/APPLICATIONS**

High Temperature Application in:

- * Primary Metals
- * Fabricated Metals
- * Chemicals
- * Glass
- * Utilities
- * Incinerators
- * Heat Treating
- * Blast Heat Recovery
- * Glass/Fire Heat Recovery
- * Automotive/Fire Protection
- * Electrical Appliance/Cost Reduction of Paint drying
- * Recovery Systems
- * Steam Reformer Tubes
- * Steam Cracker Coils
- * Indirect Coal Fired Gas Turbine

NEW INDUSTRIES/APPLICATIONS

- * Waste Incinerators
- * Fluid Bed Boilers
- * Fuel (low quality) Utilization
- * Chemical (gas/liq, liq/liq)
- * Soaking Pit Furnace

TABLE 26**BREAKDOWN OF THE 1990 DOLLAR SALES VOLUME OF HEAT EXCHANGER TUBES****A: BREAKDOWN BY TYPE OF MATERIAL**

MATERIAL	Number of Resps.	Low	Mean	Median	High
Metal	25	50.0	86.7	90.0	100.0
Ceramics	24	0.0	8.9	9.0	30.0
Composites	23	0.0	5.3	2.0	35.0

B: BREAKDOWN BY INDUSTRY

INDUSTRY	Number of Resps.	Low	Mean	Median	High
Primary Metals	13	3.0	19.1	20.0	55.0
Fabricated Metals	15	2.0	16.1	15.0	50.0
Chemicals	12	10.0	28.1	30.0	45.0
Glass	14	2.0	9.1	5.0	30.0
Utility	14	0.0	23.1	20.0	50.0
Incinerators	13	0.0	6.1	5.0	20.0

TABLE 27**ESTIMATED ANNUAL GROWTH RATE OF HEAT EXCHANGER TUBE SALES****A. Growth Rate Without Any Changes In Available Heat Exchanger Tube Materials**

Period	1990-91	1992-93	1994-95	1995-2000	2000-2005
No. of Respondents	16	16	16	16	16
Estimated Growth Rates (%)					
Low	-1.0	-1.0	1.0	1.0	1.0
Mean	5.8	7.4	7.8	8.3	7.6
High	20.0	20.0	25.0	25.0	25.0
Median	5.0	5.0	5.0	5.0	5.0

B. Growth Rate Assuming Introduction of SCWRA Tubes In 1992

Period	1990-91	1992-93	1994-95	1995-2000	2000-2005
No. of Respondents	13	13	14	14	14
Estimated Growth Rates (%)					
Low	-1.0	-1.0	1.0	1.0	1.0
Mean	6.2	7.1	9.1	9.2	9.4
High	20.0	20.0	30.0	30.0	30.0
Median	5.0	5.0	5.0	8.0	8.0

TABLE 28**ESTIMATE OF MARKET SHARE****A: MARKET SHARE ESTIMATE OF EACH TYPE OF MATERIAL**

Year	1991	1992	1993	1995	2000	2005	Number of Resps.
Metals	90%	88%	85%	81%	75%	69%	17
Ceramics	7.5%	8.1%	8.5%	8.7%	10.4%	13%	16
Current Composites	4.5%	4%	4.4%	7.5%	9.1%	10.6%	14
Whisker-reinforced Alumina	0%	1.7%	3.4%	5%	6.6%	7.6%	14
TOTAL	100	100	100	100	100	100	

B: MARKET SHARE ESTIMATE OF SCWRA TUBES BY INDUSTRY

Year	1991	1992	1993	1995	2000	2005	Number of Resps.
Primary Metals	0%	.3%	0%	.7%	1.7%	3.8%	8
Fabricated Metals	0%	.1%	1%	2.1%	3%	3.72%	8
Chemicals	0%	.5%	1.2%	1.7%	2.7%	4.3%	8
Glass	0%	1.3%	1.3%	1.9%	3%	4.8%	9
Utility	0%	.1%	1%	2.5%	3.5%	4.8%	8
Incinerators	0%	.1%	1%	2.5%	3.5%	4.8%	8
Others	0%						

TABLE 29

MARKET SHARE AND VOLUME FORECASTS

<u>Year</u>	<u>Total</u>	<u>Total</u>	<u>Metal</u>	<u>Ceram.</u>	<u>Comp.</u>	<u>SCWRA</u>	<u>New</u>	<u>Replace</u>
	<u>-SCWRA</u> <u>+SCWRA</u>							
1990								
Market Share in %			86.7%	8.9%	5.3%	0.0%		
Volume Index	100	100	86.7	8.9	5.3	0.0	0.0	0.0
1991								
Market Share in %			90.0%	7.5%	5.3%	0.0%		
Volume Index	106	106	95.2	7.9	5.6	0.0	0.0	0.0
1992								
Market Share in %			88.0%	8.1%	4.0%	1.7%		
Volume Index	113.6	113.3	99.7	9.2	4.5	1.9	-0.3	2.2
1993								
Market Share in %			85.0%	8.5%	4.4%	3.4%		
Volume Index	122	121.4	103.2	10.3	5.3	4.1	-0.7	4.8
1994								
Market Share in %			81.0%	8.7%	7.5%	5.0%		
Volume Index	131.6	132.4	107.2	11.5	9.9	6.6	0.8	5.8
1995								
Market Share in %			81.0%	8.7%	7.5%	5.0%		
Volume Index	141.8	144.4	117.0	12.6	10.8	7.2	2.6	4.6
1996								
Market Share in %			75.0%	10.4%	9.1%	6.6%		
Volume Index	153.6	157.7	118.3	16.4	14.4	10.4	4.1	6.3
1997								
Market Share in %			75.0%	10.4%	9.1%	6.6%		
Volume Index	166.3	172.3	129.2	17.9	15.7	11.4	5.9	5.5
1998								
Market Share in %			75.0%	10.4%	9.1%	6.6%		
Volume Index	180.1	188.1	141.1	19.6	17.1	12.4	8.0	4.5
1999								
Market Share in %			75.0%	10.4%	9.1%	6.6%		
Volume Index	195.1	205.4	154.1	21.4	18.7	13.6	10.3	3.2
2000								
Market Share in %			75.0%	10.4%	9.1%	6.6%		
Volume Index	211.3	224.3	168.2	23.3	20.4	14.8	13.0	1.8
2001								
Market Share in %			69.0%	13.0%	10.6%	7.6%		
Volume Index	227.3	245.4	169.3	31.9	26.0	18.6	18.0	0.6
2002								
Market Share in %			69.0%	13.0%	10.6%	7.6%		
Volume Index	244.5	264.0	182.2	34.3	28.0	20.1	19.4	0.7
2003								
Market Share in %			69.0%	13.0%	10.6%	7.6%		
Volume Index	163.2	288.9	199.3	37.6	30.6	22.0	25.6	0.0
2004								
Market Share in %			69.0%	13.0%	10.6%	7.6%		
Volume Index	183.2	316.0	218.0	41.1	33.5	24.0	32.8	0.0
2005								
Market Share in %			69.0%	13.0%	10.6%	7.6%		
Volume Index	304.7	345.7	238.5	44.9	36.6	26.3	41.0	0.0

TABLE 30**MARKET SHARE AND DOLLAR VOLUME FORECASTS****TOTAL SHELL AND TUBES HEAT-EXCHANGER SALES IN 1990 = \$821 MILLION**

(Estimate from Frost and Sullivan)

Fig. in \$ Millions**A. Low Estimate Tubes = 40% of the Total Shell & Tubes sales**

<u>Year</u>	<u>TOTAL MARKET</u>		<u>Metal</u>	<u>Ceram.</u>	<u>Comp.</u>	<u>SCWRA</u>
	<u>-SCWRA</u>	<u>+SCWRA</u>				
1990	328.4	328.4	284.7	29.2	17.4	0.0
1992	373.2	372.1	327.5	30.1	14.9	6.3
1995	465.7	474.4	384.2	41.3	35.6	23.7
2000	693.9	736.6	552.4	76.6	67.0	45.6
2005	1000.8	1135.3	783.4	147.6	120.3	86.3

B. Most Likely Estimate Tubes = 50% of the Total Shell & Tubes sales

<u>Year</u>	<u>TOTAL MARKET</u>		<u>Metal</u>	<u>Ceram.</u>	<u>Comp.</u>	<u>SCWRA</u>
	<u>-SCWRA</u>	<u>+SCWRA</u>				
1990	410.5	410.5	355.9	36.5	21.7	0.0
1992	466.4	465.1	409.3	37.7	18.6	7.9
1995	582.2	593.0	480.3	51.6	44.5	29.6
2000	867.3	920.7	690.6	95.8	83.8	60.8
2005	1251.0	1419.1	979.2	184.5	150.4	107.9

C. High Estimate Tubes = 60% of the Total Shell & Tubes sales

<u>Year</u>	<u>TOTAL MARKET</u>		<u>Metal</u>	<u>Ceram.</u>	<u>Comp.</u>	<u>SCWRA</u>
	<u>-SCWRA</u>	<u>+SCWRA</u>				
1990	492.6	492.6	427.1	43.8	26.1	0.0
1992	559.7	558.2	491.2	45.2	22.3	9.5
1995	698.6	711.6	576.4	61.9	53.4	35.6
2000	1040.8	1104.9	828.7	114.9	100.5	72.9
2005	1501.2	1703.0	1175	221.4	180.5	129.4

APPENDIX A:
STAGE 1 QUESTIONNAIRE

THE UNIVERSITY OF
ARIZONA
TUCSON ARIZONA

College of Business and
Public Administration
Department of Marketing
Karl Eller Graduate School of Management

Room 347, Harvill
Tucson, Arizona 85721
(602) 621-7479

November 23, 1990

Mr. M. K. Steffens

Dear Mr. Steffens:

I am writing to solicit your help in a Delphi study being conducted jointly by the Department of Marketing, University of Arizona and Tucson-based Materials and Electrochemical Research Corporation, Inc. The purpose of the study is to develop a realistic assessment of the desirable technical features and market potential for silicon carbide whisker-reinforced alumina tubes for use in heat-exchangers. The study is sponsored by the Department of Energy through the Oak Ridge National Laboratory.

A Delphi study is a special type of survey conducted to develop a basic understanding of a complex, technical topic on which documented information is sparse, but where the collective opinions of knowledgeable experts has significant value. Based on our research and information supplied by our sponsors, we have identified a small group of individuals in industry, universities and government whose level of expertise in heat-exchanger technology and related applications qualifies them to participate in this study.

The enclosed questionnaire is the first stage of a two stage survey. It is relatively long but covers a topic that we believe is of considerable professional interest to you. We will summarize the responses to this first questionnaire and return a report to you in a few weeks. The report will be accompanied by a shorter, second questionnaire requesting some additional comments and input. The final survey results will be sent first to all study participants. A technical report will be published later with only the aggregate results. Your identity will not be revealed and all responses will remain anonymous.

The research report that you will receive by participating will be a valuable collective expert assessment of the technology, desirable product specifications and market potential for heat-exchanger tube materials. The results will help industry and government officials improve product design and market development decisions with considerable long term benefits to the industry. You will also be helping academic researchers at the University of Arizona test the application of the Delphi survey method for technology forecasting and market assessments.

Given the small number of qualified and knowledgeable individuals, I sincerely hope you will participate in this survey. Instructions for completing and returning the questionnaire are enclosed. I will appreciate receiving your completed questionnaire as soon as possible and no later than December 14, 1990.

Should you have any questions about the study, please do not hesitate to contact me at the above address or phone number. I look forward to hearing from you and to your participation in the study.

Sincerely,

Dipankar Chakravarti
Professor of Marketing & Psychology
Head, Department of Marketing

PRODUCT TECHNOLOGY AND MARKET ASSESSMENT FOR SILICON CARBIDE WHISKER-REINFORCED ALUMINA HEAT-EXCHANGER TUBES

A Two-Stage Delphi Survey

INTRODUCTION

This Delphi Study aims to develop a realistic assessment of the desirable technical features and market potential for silicon carbide whisker-reinforced alumina tubes for use in heat exchangers. We wish to determine the required specifications for products of this type and also estimate the adoption rate of such tubes for use in heat-exchangers in various industries. The survey is sponsored by the Department of Energy through the Oak Ridge National Laboratory. The results will help industry and government officials improve product design and market development decisions.

PROCEDURE

The survey respondents have been selected from industry, universities and government labs based on their expertise and professional interest in the improvement of heat exchanger technology. Their collective responses will be a valuable assessment of the technology and market potential for the product.

The survey will be conducted in two stages. The enclosed questionnaire is the first stage. We will summarize the responses to this first questionnaire and return a report to you in a few weeks. The report will be accompanied by a second questionnaire requesting additional comments and input. The final survey results will be sent first to all the respondents. A technical report will be published later but with only the aggregate results. The respondents' identity will not be revealed and all responses will remain anonymous.

This questionnaire has four sections. The first section asks for your perception of the importance of various performance factors of heat exchanger tubes in specific industries. The second section asks you to indicate what you feel will be desirable specifications for products of this type. The third section explores your perceptions of the strengths and weaknesses of whisker-reinforced alumina tubes as substitutes for other heat exchanger tube materials and for new market applications. The final section asks for your estimates of the market potential and projected market development for the technology.

Please read and answer each question carefully. The value of the study depends on your considered responses. We are interested in your estimates even if they are subjective. It is critical that you return the questionnaire even if you cannot answer all the questions.

TIMING OF THE SURVEY

Please keep a copy of the completed questionnaire for your files and return this original using the enclosed stamped reply envelope. **We will greatly appreciate receiving your completed responses as soon as possible and no later than December 14, 1990.** This will give us the time to tabulate your responses quickly. The summary report and the second questionnaire will be sent to you shortly thereafter.

Thank you for your participation.

Page 1

SECTION A: PERFORMANCE FACTORS AND THEIR IMPORTANCE BY INDUSTRY

In this first section, we are interested in your perceptions of the relative importance of several performance factors that may be used to evaluate and select heat-exchanger tubes in each of a number of industries. A list of potential factors is given below. For each factor, please circle the number that you believe best represents its relative importance in the selection of heat exchanger tubes in the industry. If you believe that the list should include other factors, please write these down in the spaces provided and rate them along with the other factors. Please answer each question to the best of your ability.

1. PRIMARY METALS (FERROUS AND NON-FERROUS) INDUSTRY
(STANDARD INDUSTRIAL CLASSIFICATION (SIC) CODE # 3300)

<u>PERFORMANCE FACTOR</u>	<u>RELATIVE IMPORTANCE</u>						
	Not Important			Very Important			
High Temperature Capability	1	2	3	4	5	6	7
High Thermal Effectiveness	1	2	3	4	5	6	7
High Thermal Conductivity	1	2	3	4	5	6	7
High Thermal Shock Resistance	1	2	3	4	5	6	7
High Pressure Capability	1	2	3	4	5	6	7
Corrosion Resistance	1	2	3	4	5	6	7
Low Leakage (through tube)	1	2	3	4	5	6	7
Low Leakage (at joints)	1	2	3	4	5	6	7
Reliability	1	2	3	4	5	6	7
Durability (Life)	1	2	3	4	5	6	7
Low Capital (installed) Cost	1	2	3	4	5	6	7
Low Tube Cost	1	2	3	4	5	6	7
Low Maintenance Cost	1	2	3	4	5	6	7
Ease of joining	1	2	3	4	5	6	7
Ease of handling/installation	1	2	3	4	5	6	7
Other factors (Please indicate):							
	1	2	3	4	5	6	7
	1	2	3	4	5	6	7

2. FABRICATED METAL (HEAT-TREATING) INDUSTRY: (SIC CODE # 3400)

<u>PERFORMANCE FACTOR</u>	<u>RELATIVE IMPORTANCE</u>						
	Not Important			Very Important			
High Temperature Capability	1	2	3	4	5	6	7
High Thermal Effectiveness	1	2	3	4	5	6	7
High Thermal Conductivity	1	2	3	4	5	6	7
High Thermal Shock Resistance	1	2	3	4	5	6	7
High Pressure Capability	1	2	3	4	5	6	7
Corrosion Resistance	1	2	3	4	5	6	7
Low Leakage (through tube)	1	2	3	4	5	6	7
Low Leakage (at joints)	1	2	3	4	5	6	7
Reliability	1	2	3	4	5	6	7
Durability (Life)	1	2	3	4	5	6	7
Low Capital (installed) Cost	1	2	3	4	5	6	7
Low Tube Cost	1	2	3	4	5	6	7
Low Maintenance Cost	1	2	3	4	5	6	7
Ease of joining	1	2	3	4	5	6	7
Ease of handling/installation	1	2	3	4	5	6	7
Other factors (Please indicate):							
	1	2	3	4	5	6	7
	1	2	3	4	5	6	7

Page 2

As on the previous page, please rate the relative importance of the performance factors for the two industries listed below.

3. CHEMICAL INDUSTRY (SIC CODE # 2800)

<u>PERFORMANCE FACTOR</u>	<u>RELATIVE IMPORTANCE</u>						
	Not Important			Very Important			
High Temperature Capability	1	2	3	4	5	6	7
High Thermal Effectiveness	1	2	3	4	5	6	7
High Thermal Conductivity	1	2	3	4	5	6	7
High Thermal Shock Resistance	1	2	3	4	5	6	7
High Pressure Capability	1	2	3	4	5	6	7
Corrosion Resistance	1	2	3	4	5	6	7
Low Leakage (through tube)	1	2	3	4	5	6	7
Low Leakage (at joints)	1	2	3	4	5	6	7
Reliability	1	2	3	4	5	6	7
Durability (Life)	1	2	3	4	5	6	7
Low Capital (Installed) Cost	1	2	3	4	5	6	7
Low Tube Cost	1	2	3	4	5	6	7
Low Maintenance Cost	1	2	3	4	5	6	7
Ease of joining	1	2	3	4	5	6	7
Ease of handling/installation	1	2	3	4	5	6	7
Other factors (Please indicate):							
	1	2	3	4	5	6	7
	1	2	3	4	5	6	7

4. GLASS INDUSTRY (SIC CODE # 3200)

<u>PERFORMANCE FACTOR</u>	<u>RELATIVE IMPORTANCE</u>						
	Not Important			Very Important			
High Temperature Capability	1	2	3	4	5	6	7
High Thermal Effectiveness	1	2	3	4	5	6	7
High Thermal Conductivity	1	2	3	4	5	6	7
High Thermal Shock Resistance	1	2	3	4	5	6	7
High Pressure Capability	1	2	3	4	5	6	7
Corrosion Resistance	1	2	3	4	5	6	7
Low Leakage (through tube)	1	2	3	4	5	6	7
Low Leakage (at joints)	1	2	3	4	5	6	7
Reliability	1	2	3	4	5	6	7
Durability (Life)	1	2	3	4	5	6	7
Low Capital (Installed) Cost	1	2	3	4	5	6	7
Low Tube Cost	1	2	3	4	5	6	7
Low Maintenance Cost	1	2	3	4	5	6	7
Ease of joining	1	2	3	4	5	6	7
Ease of handling/installation	1	2	3	4	5	6	7
Other factors (Please indicate):							
	1	2	3	4	5	6	7
	1	2	3	4	5	6	7

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As on the previous two pages, please rate the relative importance of the performance factors for the two industries listed below.

5. UTILITY INDUSTRY (SIC CODE # 4900)

<u>PERFORMANCE FACTOR</u>	<u>RELATIVE IMPORTANCE</u>						
	Not Important			Very Important			
High Temperature Capability	1	2	3	4	5	6	7
High Thermal Effectiveness	1	2	3	4	5	6	7
High Thermal Conductivity	1	2	3	4	5	6	7
High Thermal Shock Resistance	1	2	3	4	5	6	7
High Pressure Capability	1	2	3	4	5	6	7
Corrosion Resistance	1	2	3	4	5	6	7
Low Leakage (through tube)	1	2	3	4	5	6	7
Low Leakage (at joints)	1	2	3	4	5	6	7
Reliability	1	2	3	4	5	6	7
Durability (Life)	1	2	3	4	5	6	7
Low Capital (installed) Cost	1	2	3	4	5	6	7
Low Tube Cost	1	2	3	4	5	6	7
Low Maintenance Cost	1	2	3	4	5	6	7
Ease of joining	1	2	3	4	5	6	7
Ease of handling/installation	1	2	3	4	5	6	7
Other factors (Please indicate):							
	1	2	3	4	5	6	7
	1	2	3	4	5	6	7

6. INCINERATOR INDUSTRY (SIC CODE # 4950)

<u>PERFORMANCE FACTOR</u>	<u>RELATIVE IMPORTANCE</u>						
	Not Important			Very Important			
High Temperature Capability	1	2	3	4	5	6	7
High Thermal Effectiveness	1	2	3	4	5	6	7
High Thermal Conductivity	1	2	3	4	5	6	7
High Thermal Shock Resistance	1	2	3	4	5	6	7
High Pressure Capability	1	2	3	4	5	6	7
Corrosion Resistance	1	2	3	4	5	6	7
Low Leakage (through tube)	1	2	3	4	5	6	7
Low Leakage (at joints)	1	2	3	4	5	6	7
Reliability	1	2	3	4	5	6	7
Durability (Life)	1	2	3	4	5	6	7
Low Capital (installed) Cost	1	2	3	4	5	6	7
Low Tube Cost	1	2	3	4	5	6	7
Low Maintenance Cost	1	2	3	4	5	6	7
Ease of joining	1	2	3	4	5	6	7
Ease of handling/installation	1	2	3	4	5	6	7
Other factors (Please indicate):							
	1	2	3	4	5	6	7
	1	2	3	4	5	6	7

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SECTION B: DESIRABLE PERFORMANCE SPECIFICATIONS FOR HEAT-EXCHANGER TUBES

In this section, we are interested in your assessments of the desirable performance specifications for heat-exchanger tubes in each of the industries we considered earlier. This information will be used to develop appropriate specifications for the proposed silicon carbide whisker-reinforced alumina tubes. Please answer each question to the best of your ability.

9. Please rate your relative familiarity with performance requirements and technical specifications of heat-exchanger tubes in the following industries.

INDUSTRY	Not Familiar				Familiar		
Primary Metals	1	2	3	4	5	6	7
Fabricated Metals	1	2	3	4	5	6	7
Chemicals	1	2	3	4	5	6	7
Glass	1	2	3	4	5	6	7
Utilities	1	2	3	4	5	6	7
Incinerators	1	2	3	4	5	6	7
Other (See Q7) _____	1	2	3	4	5	6	7

10. Please indicate whether or not you are familiar (i.e., have some knowledge and/or usage experience) with each of the following types of heat exchanger tube materials. Please name the specific material(s) with which you have experience.

	Check if familiar	Names of Materials
Metals	()	_____
Ceramic	()	_____
Metal & Ceramic-based Composites	()	_____

11. Please indicate what you believe is the required range of temperature withstanding capability for heat-exchanger tubes in each of the industries named below. For each industry, please mark two boxes that include the lower and upper bounds of the range as closely as possible. For example, if the range you wish to indicate is between 750 and 1600 ($^{\circ}$ F), mark the 500 and 1750 boxes.

INDUSTRY	TEMPERATURE RANGE (DEGREES FARENHEIT)									
	<500	500	1000	1250	1500	1750	2000	2250	2500	>2500
Primary Metals	()	()	()	()	()	()	()	()	()	()
Fabricated Metals	()	()	()	()	()	()	()	()	()	()
Chemicals	()	()	()	()	()	()	()	()	()	()
Glass	()	()	()	()	()	()	()	()	()	()
Utilities	()	()	()	()	()	()	()	()	()	()
Incinerators	()	()	()	()	()	()	()	()	()	()
Other (See Q7) _____	()	()	()	()	()	()	()	()	()	()

12. If you can state the range of required temperature withstanding capability more specifically than you did in Question 11 above, please do so below:

INDUSTRY	TEMPERATURE RANGE (DEGREES FARENHEIT)	
	Lower bound	Upper bound
Primary Metals	_____	_____
Fabricated Metals	_____	_____
Chemicals	_____	_____
Glass	_____	_____
Utilities	_____	_____
Incinerators	_____	_____
Other (See Q7) _____	_____	_____

13. Please indicate what you believe is the normal range of thermal effectiveness available with current heat-exchanger in each of the following industries. For each industry, please mark two boxes that include the lower and upper bounds of the range as closely as possible.

[illegible]

14. Keeping in mind the normal operating temperatures that are applicable, please indicate what you believe is the normal range of thermal conductivity of heat-exchanger tube material used in each of the following industries. For each industry, please mark two boxes that include the lower and upper bounds of the range as closely as possible.

[illegible]

15. Please indicate what you believe is the normal range of temperature cycling (thermal shock) that a heat-exchanger tube must withstand in each of the industries named below. For each industry, please mark two boxes that include the lower and upper bounds of the range as closely as possible.

[illegible]

16. Keeping in mind the pressure drops involved during normal operation, please indicate what you believe is the required range of pressure capability for heat-exchanger tubes in each of the following industries. For each industry, please mark two boxes that include the lower and upper bound of the range as closely as possible.

INDUSTRY	PRESSURE CAPABILITY RANGE (Pounds per sq. inch)					
	<50	50	100	150	200	>200
Primary Metals	()	()	()	()	()	()
Fabricated Metals	()	()	()	()	()	()
Chemicals	()	()	()	()	()	()
Glass	()	()	()	()	()	()
Utilities	()	()	()	()	()	()
Incinerators	()	()	()	()	()	()
Other (See Q7)	()	()	()	()	()	()

INDUSTRY

CORROSIVE MATERIAL

CONTINUOUS MATERIALS					
Mineral Acids	Flue Gases	Slag	Oxida- tion	Molten Metals	Other (please indicate)

Primary Metals	()	()	()	()	()	()	_____
Fabricated Metals	()	()	()	()	()	()	_____
Chemicals	()	()	()	()	()	()	_____
Glass	()	()	()	()	()	()	_____
Utilities	()	()	()	()	()	()	_____
Incinerators	()	()	()	()	()	()	_____
Other (See Q7)	()	()	()	()	()	()	_____

18. Please indicate what you believe is a normally acceptable leakage rate (through the tube) for heat-exchanger tubes in each of the following industries. For a number that appears at the ends of two ranges, please mark the box for the lower range (i.e., 0.1-0.5).

INDUSTRY

LEAKAGE RATE (PERCENT)

<.1 0.1-0.5 0.5-1.0 1.0-1.5 1.5-2.0 >2.0

Primary Metals	()	()	()	()	()	()
Fabricated Metals	()	()	()	()	()	()
Chemicals	()	()	()	()	()	()
Glass	()	()	()	()	()	()
Utilities	()	()	()	()	()	()
Incinerators	()	()	()	()	()	()
Other (See Q7)	()	()	()	()	()	()

19. Please indicate what you believe is a normally acceptable leakage rate (at the joint) for heat-exchanger tubes in each of the following industries. For a number at the end of a range, please mark the box for the lower range.

INDUSTRY

LEAKAGE RATE (PERCENT)

<1	1-5	5-10	10-15	15-20	20-25	>25
----	-----	------	-------	-------	-------	-----

Primary Metals	()	()	()	()	()	()
Fabricated Metals	()	()	()	()	()	()
Chemicals	()	()	()	()	()	()
Glass	()	()	()	()	()	()
Utilities	()	()	()	()	()	()
Incinerators	()	()	()	()	()	()
Other (See Q7)	()	()	()	()	()	()

20. Please indicate the sizes (inner diameters) of heat-exchanger tubes that you believe are used in each of the following industries. Please mark as many sizes as are applicable.

INDUSTRY

INNER DIAMETER (INCHES)

0.5-1 1-2 2-4 4-6 6-10 >10

Primary Metals	()	()	()	()	()	()
Fabricated Metals	()	()	()	()	()	()
Chemicals	()	()	()	()	()	()
Glass	()	()	()	()	()	()
Utilities	()	()	()	()	()	()
Incinerators	()	()	()	()	()	()
Other (See Q7)	()	()	()	()	()	()

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21. Please indicate the lengths of heat-exchanger tubes that you believe are used in each of the following industries. Please mark as many lengths as are applicable.

INDUSTRY	LENGTHS (FEET)					
	<1	1-3	3-6	6-10	10-20	>20
Primary Metals	()	()	()	()	()	()
Fabricated Metals	()	()	()	()	()	()
Chemicals	()	()	()	()	()	()
Glass	()	()	()	()	()	()
Utilities	()	()	()	()	()	()
Incinerators	()	()	()	()	()	()
Other (See Q7) _____	()	()	()	()	()	()

22. Please indicate the shapes (enhancements) of heat-exchanger tubes that you believe are used in each of the following industries. Please mark all shapes that are applicable.

INDUSTRY	TUBES	FIN PLATES	FIN TUBES	OTHER (PLEASE INDICATE)
Primary Metals	()	()	()	_____
Fabricated Metals	()	()	()	_____
Chemicals	()	()	()	_____
Glass	()	()	()	_____
Utilities	()	()	()	_____
Incinerators	()	()	()	_____
Other (See Q7) _____	()	()	()	_____

23. Please indicate what you believe are the appropriate approaches for joining composite ceramic tubes to metal components for heat-exchanger applications in each of the industries named below. Please check as many boxes as may apply. If you are aware of other joining approaches that are used/feasible, please indicate what they are in the space provided.

INDUSTRY	Mechanical	Thermal Bonding	Other (Please indicate)
Primary Metals	()	()	() _____
Fabricated Metals	()	()	() _____
Chemicals	()	()	() _____
Glass	()	()	() _____
Utilities	()	()	() _____
Incinerators	()	()	() _____
Other (See Q7) _____	()	()	() _____

24. Please indicate what you believe is the normally expected operating life for heat-exchanger tubes used in each of the following industries.

INDUSTRY	LIFETIME IN MONTHS					
	<3	3-6	6-12	12-24	24-36	>36
Primary Metals	()	()	()	()	()	()
Fabricated Metals	()	()	()	()	()	()
Chemicals	()	()	()	()	()	()
Glass	()	()	()	()	()	()
Utilities	()	()	()	()	()	()
Incinerators	()	()	()	()	()	()
Other (See Q7) _____	()	()	()	()	()	()

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25. We are interested in determining the normally acceptable mechanical properties for heat-exchanger tubes used in various industries. For each property named in Parts A, B and C below, please indicate what you believe is a normally acceptable rating level for heat exchanger tubes. Please keep in mind the normal operating temperatures for each industry.

A. Strength rating

INDUSTRY	Strength Rating in Kilo-Pounds/sq. in. (Kpsi)						
	20-35	35-50	50-65	65-80	80-95	95-110	>110
Primary Metals	()	()	()	()	()	()	()
Fabricated Metals	()	()	()	()	()	()	()
Chemicals	()	()	()	()	()	()	()
Glass	()	()	()	()	()	()	()
Utilities	()	()	()	()	()	()	()
Incinerators	()	()	()	()	()	()	()
Other (See Q7) _____	()	()	()	()	()	()	()

B. Fracture toughness rating

INDUSTRY	Fracture Toughness Rating (Kpsi.in ^{1/2})				
	2-5	5-10	10-15	15-20	>20
Primary Metals	()	()	()	()	()
Fabricated Metals	()	()	()	()	()
Chemicals	()	()	()	()	()
Glass	()	()	()	()	()
Utilities	()	()	()	()	()
Incinerators	()	()	()	()	()
Other (See Q7) _____	()	()	()	()	()

C. Reliability rating

INDUSTRY	Weibull Modulus			
	10-15	15-20	20-25	>25
Primary Metals	()	()	()	()
Fabricated Metals	()	()	()	()
Chemicals	()	()	()	()
Glass	()	()	()	()
Utilities	()	()	()	()
Incinerators	()	()	()	()
Other (See Q7) _____	()	()	()	()

26. What would you estimate to be the average heat recovery capability and the average cost (capital and installation) of installed heat-exchanger systems that you are aware of in each of the following industries ?

INDUSTRY	HEAT RECOVERY (MILLION BTU/HR)	CAPITAL & INSTALLATION COST (\$ THOUSANDS)	TYPE OF FUEL USED
Primary Metals	_____	_____	_____
Fabricated Metals	_____	_____	_____
Chemicals	_____	_____	_____
Glass	_____	_____	_____
Utilities	_____	_____	_____
Incinerators	_____	_____	_____
Other (See Q7) _____	_____	_____	_____

INDUSTRY

Primary Metals
Fabricated Metals
Chemicals
Glass
Utilities
Incinerators
Other (See Q7)

INDUSTRY

[illegible]

29. Are there any other critical performance features that are used in the evaluation of heat exchanger tubes in each of the industries above? Please use the space below to identify these factors and the desirable specifications on these dimensions.

This image shows a single sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

C. SUBSTITUTION AND REPLACEMENT OF OTHER HEAT-EXCHANGER TUBE MATERIALS

In this section we are interested in assessing the degree to which the proposed silicon carbide whisker-reinforced alumina tubes would be appropriate as substitutes or replacements for other materials currently used for heat-exchanger tubes. Even though many of the assessments that follow may be based upon your subjective opinions, these are of great interest to us. Therefore, please answer each questions to the best of your ability.

30. Please indicate below your perception of the current degree of usage of the following types of heat-exchanger tube material in the industries listed. Please consider the diversity of usage situations and products in your answer. The term "composite" pertains to both metal and ceramic-based composites only.

INDUSTRY/MATERIAL		No Usage			High Usage	
Primary Metals	Metals	1	2	3	4	5
	Ceramics	1	2	3	4	5
	Composites	1	2	3	4	5
Fabricated Metals	Metals	1	2	3	4	5
	Ceramics	1	2	3	4	5
	Composites	1	2	3	4	5
Chemicals	Metals	1	2	3	4	5
	Ceramics	1	2	3	4	5
	Composites	1	2	3	4	5
Glass	Metals	1	2	3	4	5
	Ceramics	1	2	3	4	5
	Composites	1	2	3	4	5
Utilities	Metals	1	2	3	4	5
	Ceramics	1	2	3	4	5
	Composites	1	2	3	4	5
Incinerators	Metals	1	2	3	4	5
	Ceramics	1	2	3	4	5
	Composites	1	2	3	4	5
Other (See Q7)	Metals	1	2	3	4	5
	Ceramics	1	2	3	4	5
	Composites	1	2	3	4	5

31. Please Identify (name) the key types of heat-exchanger tube materials that you considered in responding to the question above.

[illegible]

Please read the following description carefully and then answer the questions that follow.

Consider the proposed silicon carbide whisker-reinforced alumina tube for use in heat-exchangers. Reinforcement with silicon carbide whiskers will greatly improve the strength and toughness of the alumina tubes at room temperature as well as at higher temperatures. The anticipated technical features and performance characteristics of the material are:

Temperature Capability:	2200°F
Thermal conductivity:	1.69 BTU/hr.in.°F at room temperature 0.48 BTU/hr.in.°F at 2200°F
Thermal shock resistance:	Will withstand temperature cycling over ranges of $T_c > 1500^\circ\text{F}$.
Corrosion resistance:	Resistant to all mineral acids, most flue gases, slags etc. Oxidation resistant to 2200°F. Can withstand molten metals, e.g., magnesium, aluminum, copper and steel.
Leakage rate:	< 0.1% through the tube. < 10% through seals and joints
Reliability:	Strength > 85 Kpsi Fracture toughness > 6 Kpsi.in ^{1/2} Weibull modulus of 20
Durability (life):	At least twice that of Silicon Carbide

Thus, relative to monolithic ceramics, the new silicon carbide whisker-reinforced alumina composite will have significantly better temperature capabilities and thermal shock resistance. Also, silicon carbide has higher thermal conductivity than alumina. Hence, the new composite will have higher thermal conductivity than alumina tubes leading to more efficient heat recovery. In addition, the material's higher strength and toughness will also significantly improve its reliability and durability. Overall, these features are expected to translate into reductions of at least 50% in assembly/installation and maintenance costs relative to current materials such as alumina and silicon carbide.

Tube prices vary by the type of material and specifications (e.g., diameter and length). For example, for the 2" diameter, the price of silicon carbide tubes may range between \$175 and \$260 per linear foot (lengths of 48" and 70" respectively). Prices for other ceramic tubes of similar specifications are lower (e.g., \$30-\$60 and \$20-\$30 per linear foot for alumina and mullite respectively). Corresponding prices for metal tubes may reach \$35-\$45 per linear foot, depending on the metal. With these prices in mind, we are considering \$75-\$100 per linear foot as an initial reference price for the new silicon carbide whisker-reinforced alumina tubes.

32. Given the initial reference price and keeping in mind the potential savings in assembly/installation, operations and maintenance, what is your assessment of the likelihood that such tubes will eventually substitute and replace each of the following types of heat-exchanger tubes ?

MATERIAL	Unlikely								Likely	
Metal	1	2	3	4	5	6	7	8	9	10
Ceramics	1	2	3	4	5	6	7	8	9	10
Composite	1	2	3	4	5	6	7	8	9	10

INDUSTRY	Unlikely									Likely
Primary Metals	1	2	3	4	5	6	7	8	9	10
Fabricated Metals	1	2	3	4	5	6	7	8	9	10
Chemicals	1	2	3	4	5	6	7	8	9	10
Glass	1	2	3	4	5	6	7	8	9	10
Utility	1	2	3	4	5	6	7	8	9	10
Incinerators	1	2	3	4	5	6	7	8	9	10
Other (See Q7)	1	2	3	4	5	6	7	8	9	10

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35. Given the preceding description of silicon carbide whisker-reinforced alumina tubes, please indicate the degree to which you believe that each of the following factors will be a facilitator or barrier to their use in heat-exchangers in the industries considered earlier.

PERFORMANCE FACTOR	Key Barrier							Key Facilitator						
Temperature Capability	1	2	3	4	5	6	7							
Thermal Effectiveness	1	2	3	4	5	6	7							
Thermal Conductivity	1	2	3	4	5	6	7							
Thermal Shock Resistance	1	2	3	4	5	6	7							
Pressure Capability	1	2	3	4	5	6	7							
Corrosion Resistance	1	2	3	4	5	6	7							
Leakage (through tube)	1	2	3	4	5	6	7							
Leakage (at joints)	1	2	3	4	5	6	7							
Reliability	1	2	3	4	5	6	7							
Durability (Life)	1	2	3	4	5	6	7							
Capital (installed) Cost	1	2	3	4	5	6	7							
Tube Cost	1	2	3	4	5	6	7							
Maintenance Cost	1	2	3	4	5	6	7							
Ease/Difficulty of Joining	1	2	3	4	5	6	7							
Ease/Difficulty of Handling/Installation	1	2	3	4	5	6	7							
Other factors (Please indicate):														
	1	2	3	4	5	6	7							
	1	2	3	4	5	6	7							

36. For each industry named, how may one overcome the key barriers to acceptance (if any) that you identified above ?

Primary Metals: _____

Fabricated Metals: _____

Chemicals: _____

Glass: _____

Utility: _____

Incinerators: _____

Other (See Q7): _____

SECTION D: CURRENT MARKET POTENTIAL AND PROJECTED MARKET DEVELOPMENT

Finally, in this section, we are interested in your estimates of current market potential and projected market development. In answering these questions, please keep in mind the features and benefits of silicon carbide whisker-reinforced alumina tubes described earlier. As before, we are interested in your estimates even if they are based upon your subjective opinions. Therefore, please answer each question to the best of your ability.

37. Please provide your best estimate of the total volume of heat-exchanger tubes that will have been installed in the North American market during the year 1990. In this estimate, please take subjective consideration of the breadth of usage situations, materials and industries. If you are more comfortable providing these volume estimates in units other than dollars or linear feet, please use the space provided to do so.

	Low	Most Likely	High
Dollar Volume (millions)	_____	_____	_____
Unit Volume (Linear feet)	_____	_____	_____
Other units _____	_____	_____	_____

38. Please provide your best estimate of the average annual percentage growth rate in the total dollar volume of heat-exchanger tube material to be installed in the North American market during the periods below. In your estimate please take subjective consideration of the breadth of the usage situations, materials and industries. However, please assume that there are no changes in the basic set of available heat-exchanger tube materials during this period.

Period	1990-91	1992-93	1994-95	1995-2000	2000-2005
Growth Rate	_____ %	_____ %	_____ %	_____ %	_____ %

39. Assume now that the silicon carbide whisker-reinforced alumina heat-exchanger tube products are introduced in 1992. Please indicate your revised estimate of the average annual percentage growth rate in the total dollar volume of heat-exchanger tube material to be installed in the North American market during the periods below. Please take subjective consideration of the preceding descriptions of the product, the likely cost savings and new levels of heat recovery due to the enhanced properties of the material as well as its additional related applications in new user industries.

Period	1990-91	1992-93	1994-95	1995-2000	2000-2005
Growth Rate	_____ %	_____ %	_____ %	_____ %	_____ %

40. Please list the industries/applications in which you expect that silicon carbide whisker-reinforced alumina heat exchanger tubes may permit significant new levels of heat recovery and additional applications.

Current Industries/Applications	New Industries/Applications
_____	_____
_____	_____
_____	_____
_____	_____

41. Please divide 100 points between the following materials to reflect your best guess of the breakdown of the 1990 dollar volume of heat-exchanger tubes by type of material.

Metal	_____
Ceramic	_____
Composites	_____
TOTAL	100

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42. Please divide 100 points between the following industries to reflect your best guess of the approximate breakdown of the 1990 dollar volume of heat-exchanger tubes by industry.

Primary Metals	_____
Fabricated Metals	_____
Chemicals	_____
Glass	_____
Utility	_____
Incinerators	_____
Other (Q7)	_____
All Other	_____
TOTAL	100

43. Please indicate the market shares that you estimate will be held by each of the following types of heat-exchanger materials in each year below. In your estimates please consider likely substitution and replacement of current heat-exchanger materials and additional applications due to the enhanced properties of the silicon carbide whisker-reinforced alumina and the associated savings.

Year	1991	1992	1993	1995	2000	2005
Metals	____%	____%	____%	____%	____%	____%
Ceramics	____%	____%	____%	____%	____%	____%
Current Composites	____%	____%	____%	____%	____%	____%
Whisker-reinforced Alumina	0%	____%	____%	____%	____%	____%
TOTAL	100	100	100	100	100	100

44. Please indicate the market share that you estimate will be held by the silicon carbide whisker-reinforced alumina tubes in each industry below in each year given. In your estimates please consider the likely substitution and replacement of current heat-exchanger materials as well as additional applications due to the enhanced properties of whisker-reinforced alumina and the associated savings. (Note that we are asking you to track the share in industry over time. Hence, column totals do not sum to 100 in this case).

Year	1991	1992	1993	1995	2000	2005
Primary Metals	0%	____%	____%	____%	____%	____%
Fabricated Metals	0%	____%	____%	____%	____%	____%
Chemicals	0%	____%	____%	____%	____%	____%
Glass	0%	____%	____%	____%	____%	____%
Utility	0%	____%	____%	____%	____%	____%
Incinerators	0%	____%	____%	____%	____%	____%
Other (Q7)	0%	____%	____%	____%	____%	____%

45. Please complete the following information about yourself for classification purposes. This information will be held confidential and will not be revealed in any published report of the study.

Age: _____ years Work Experience: _____ years Highest Degree: _____

46. Please attach (tape or staple) your business card at the right of this page.

This completes the first round of the Delphi survey. Please review your answers. Keep a copy of this questionnaire for your files and return this original using the enclosed stamped return envelope. In a few weeks we will send you a summary report of the responses along with a second and final questionnaire that requests some additional comments and input.

WE THANK YOU VERY MUCH FOR YOUR COOPERATION.

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