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An Assessment of the Cost of Microwave Sintering Ceramic Tiles for Armor Applications: Phase 1 Report

Sujit Das
T. Randall Curlee

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AN ASSESSMENT OF THE COST OF MICROWAVE SINTERING CERAMIC TILES FOR ARMOR APPLICATIONS: PHASE 1 REPORT

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and
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ABSTRACT

This report documents the findings of the first of two phases of work to assess the costs of microwave sintering ceramic tiles for armor applications. In the first phase of work, the sintering component of a process-cost model was developed and used to estimate the cost of microwave sintering alumina and silicon-carbide tiles. Two microwave frequencies (i.e., 2.45 GHz and 28 GHz) are considered. The second phase of work will extend the process-cost model to include all pre- and post-sintering manufacturing steps and consider process and cost variations in these steps that may result from the adoption of microwave sintering. While the process-cost model developed for this work focuses only on the cost of the sintering step, preliminary estimates of the total cost of a microwave-sintered tile are also provided under the assumption that the costs of pre- and post-sintering steps in the production process will not be altered by the adoption of microwave sintering.

The base-case cost of microwave sintering alumina tiles is estimated to be $14.98 and $18.17/part given the use of 2.45 GHz and 28 GHz microwave power sources, respectively. The higher sintering cost in the case of a 28 GHz microwave power source results from the 28 GHz unit's lower firing heat efficiency and higher capital cost as compared to a 2.45 GHz unit. The cost of microwave sintering is estimated to be more than three times that of conventional sintering. However, the adoption of microwave sintering is not expected to drastically increase the cost of ceramic tiles. More specifically, the cost of microwave-sintered alumina tiles is estimated to be about 1.3 times higher than the cost of conventionally-sintered tiles. Note, however, that this estimate does not take into consideration any potential cost changes that microwave sintering may imply for pre- and post-sintering manufacturing steps (i.e., the subject of the second phase of work).

In the case of silicon-carbide tiles, the base-case cost of microwave sintering is estimated to be lower than the cost of conventional sintering (i.e., $39.11 and $41.66/part for 2.45 GHz and 28 GHz microwave power sources, respectively, as compared to $106.14/part for conventional sintering). The study assumes that conventional sintering contributes 45% of the total cost of producing silicon-carbide tiles (as compared to 13% in the case of alumina tiles). However, this assumption, which is based on information collected from industry experts, appears to be high and is worthy of further analysis. The lower relative cost of microwave sintering in the case of silicon carbide results in microwave-sintered tiles that are cheaper than conventionally sintered silicon-carbide tiles.

Labor is estimated to be one of the largest cost components in the case of alumina tiles. The costs of capital charges, energy, other miscellaneous inputs, and materials follow in terms of their contributions to the cost of sintering alumina. The cost of ceramic powder is not taken into consideration at the sintering step. (Rather, powder costs are incurred in the materials preparation step, which is yet to be modeled). The cost of materials, therefore, were not expected to be a major contributor to the cost of microwave sintering, and this is true in the case of alumina tiles. However, this is not true in the case of silicon-carbide tiles because of expensive insulating materials. The mixture of glassy carbon and boron nitride required during sintering (estimated to cost $66/lb) causes materials to be the largest cost component at the sintering step in the case of silicon carbide. Other than materials, the contributions of cost components to sintering cost follow the same order as is found in the case of alumina tiles.

Several sensitivity analyses of the impacts of variations in key economic and technical parameters on the costs of microwave sintering and total part cost were conducted. Those analyses indicate that costs are particularly sensitive to changes in the quantity of microwave energy required (KWh/lb) during sintering. Energy requirements are important because they influence the quantities of labor and capital required for a given production volume.

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) is currently engaged in research for the U.S. Army Tank Automobile Command (TACOM) and the Army Research Laboratory Weapons Test Directorate to determine if microwave sintering can improve the ballistic performance ranking of armor ceramics. While the performance of ceramic tiles that are sintered with microwaves may exceed the performance of conventionally-sintered tiles, microwave-sintered tiles may also cost more. This report is focused on estimating the costs of microwave-sintered armor ceramics as compared to the costs of ceramic tiles sintered using conventional methods.

The cost analysis is being done in two phases. In the first phase, which is the subject of this report, a parametric cost analysis model was developed to provide preliminary estimates of the cost of the microwave sintering step. This first phase assumed that all pre-sintering and post-sintering steps in the production of ceramic tiles are not altered by the adoption of microwave sintering. In the second phase of this work (which is at this point unfunded), the analysis will be extended to account for cost variations that may accompany the adoption of microwave sintering and occur in steps prior to and following the sintering step.

2. BACKGROUND

The last half of the 1980s saw a great deal of interest in the area of microwave sintering. Despite this recent flurry of activity, the first pioneering experiments in this field were performed as early as 1968 by Tinga and Voss (1968). With the exception of a few studies (e.g., Sutton (1988), Schubering (1983), Patterson et al. (1990), and Katz and Blake (1991)), all of the studies reported in the literature involve single, small samples. Demonstration of the simultaneous sintering of multiple samples is necessary to gain the acceptance of microwave sintering of ceramics as a viable industrial process.

The application of microwave energy for ceramic sintering offers exciting new possibilities for materials processing. In addition to improving material properties, microwave processing may reduce processing time, reduce required factory floor space for kilns, and decrease energy requirements. In order to scale this innovative technique to the industrial level, methods and hardware must be developed to produce large uniform fields to process large loads. Field gradients produced in standard products, such as the home microwave, invariably lead to hot spots and nonuniform processing. A frequency higher than 2.45 GHz is generally believed to be necessary to have a cavity of reasonable size to process large loads and to provide uniform fields. Kimrey and Janney (1988) indicate that by operating at 28 GHz, adequately uniform fields can be produced within a cavity of approximately 0.5 cubic meters in volume. They also point out that system efficiency for a given material can be optimized as a function of cavity and workpiece size, frequency, and temperature.

Little work has been done on the cost implications of microwave sintering ceramic tiles for armor applications. Mingledorff (1992), the lone identified exception to this rule, has developed a spreadsheet model to estimate a price level (i.e., in terms of $/lb) at which ceramic materials could be cost competitive with current tank armor technologies. The model examines cost and benefit tradeoffs between conventional materials and ceramics in terms of mass and space efficiencies. Unfortunately, there is little model documentation or detailed discussions of input assumptions to accompany Mingledorff's results.

This report focuses specifically on the cost of manufacturing ceramic tiles for armor applications using microwave sintering as compared to the cost of similar tiles sintered with conventional technology. The economic viability of microwave-sintered ceramic tiles will, of course, not only depend on the cost differential between the alternative sintering technologies, but also on the value of improved ballistic performance ranking. However, this report does not address the value of the marginal benefits provided by improved ballistic performance.

3. APPROACH

This study's basic approach is to utilize a process-cost model to estimate the total costs of the microwave sintering step. In the typical process-cost model, each production step involved in a particular technology is modeled individually, and the values of all inputs associated with each process are calculated by process step and for the production process as a whole. These inputs include raw materials, energy, labor, capital and equipment, and other miscellaneous expenditures, each of which is process dependent. The output of the first process step, in terms of total cost and the costs of individual inputs, becomes and input to the second production step, and so forth. Thus, at each production step the models can be used to estimate the total cost of the product at that step, the contribution of that production step to the total cost of the product at that point in production, and the contribution of each input to the total cost and to the cost of a particular production step. Das and Curlee (1988) used this approach to estimate the cost of ceramic tubes and headers used in advanced heat exchangers. In a more recent study (Das and Curlee, 1992) the process-cost approach was used to assess the contribution that lower-cost ceramic powders could make to the overall economic viability of advanced ceramic engine components. The above mentioned models and the model developed for this work are constructed within an electronic spreadsheet to provide maximum flexibility in estimating base-case costs and in conducting sensitivity analyses with respect to key technology and cost parameters.

In this work, unlike most process-cost models, only one production step is modeled -- i.e., microwave sintering. Pre-sintering and post-sintering steps -- e.g., materials preparation, casting, drying, machining, and quality control and storage -- are to be included in the second phase of this work, but are not included here. To arrive at rough preliminary estimates of the total cost of a microwave-sintered ceramic tile, a "back-of-the-envelope" method is used. More specifically, information was obtained on the estimated contribution that conventional sintering makes to the total cost of currently-available ceramic armor tiles. By extracting the estimated cost of sintering these tiles using conventional technology and inserting the estimated cost of microwave sintering, a preliminary estimate of the total cost of a microwave-sintered tile can be made. Note, however, that this method does not consider any positive or negative cost impacts that the adoption of microwave sintering will have on pre- and post-sintering steps. Further note that in previous studies [e.g., Das and Curlee (1988 and 1992)], changes in one process step have been shown to have major cost consequences for other process steps.

4. MODEL DESCRIPTION

The process-cost model developed for this work aggregates the estimated costs of five major factor inputs -- i.e., energy, materials, labor, capital, and other -- to estimate the total cost of microwave sintering. The quantities of each factor input required for the microwave sintering step and the resulting total cost of each factor input is estimated as a function of exogenously specified tile dimensions and specifications and exogenously specified relationships between factor inputs in the production process.

Unit prices of each factor input are also entered into the model. The manufacturer of tiles is assumed to be a "price taker" with respect to the per-unit costs of factor inputs. In other words, the per-unit costs of each of the factor inputs do not decrease as additional units are purchased. Economies of scale are, however, incorporated into the model. In other words, the units of some factor inputs required to produce a given quantity of tiles are assumed to decrease as the total production volume of tiles is increased. This section provides a detailed discussion of the various relationships between factor inputs and the production process embedded in the process-cost model.

4.1 PRODUCT AND PROCESS DESCRIPTION

The quantities of input factors required for the production of tiles, and therefore the costs of the tiles, depend on several key product and process parameters. These parameters include production volume, part specification, yields, cycle times, and firing methods and parameters. Annual production volume is defined in terms of number of parts per year. An armor tile is defined in terms of length, width, and thickness. The multiplicative product of the volume of an armor tile -- defined as a product of length, width, and thickness -- and the density of the ceramic material (either alumina or silicon carbide) gives the weight of an armor tile. Operating time, number of shifts/day, and number of hours/shift are entered exogenously and are important in determining the required production rate and also the total capital cost required to attain the desired annual production volume.

Production rate, V (lbs/hr) is defined as:

$$V = \frac{\text{Annual Production Volume} * \text{Part Weight}}{\text{Sintering Yield} * \text{Operating Time(days/yr)} * \text{No. Shifts/Day} * \text{No. of Hours/Shift}}$$

Yield is defined as the physical yield of the process (i.e., 1-scrap rate) and is used to calculate the amount of material that is necessary to input into each operation in order to produce the desired amount of final product at the end.

Two microwave frequencies (i.e., 2.45 GHz and 28 GHz) are considered. Capital cost, energy requirements, and firing heat efficiency are sensitive to the frequency selected. Furnace rating and packing density are particularly important microwave furnace parameters. The furnace rating is assumed to be 50KW, with several of these units operating simultaneously in parallel to satisfy a

specific yearly production volume. Increases in yearly production volume are assumed to be met by the purchase of additional 50KW units rather than the purchase of larger units. Packing density is defined as a ratio of total applicator volume to part volume. Packing density is used in the calculation of the quantities of insulation and inert gas atmosphere necessary during sintering.

4.2 FACTOR INPUTS

4.2.1 Energy

The process-cost model allows the price of electricity -- the only energy input considered at the sintering step -- to be entered exogenously to reflect regional differences in electricity prices. Microwave energy required for sintering in KWh/lb and firing heat efficiency determine the total quantity of electricity required in the sintering step. Microwave energy required (KWh/lb) can either be input directly if known; otherwise it can be calculated from the actual power versus time sintering cycle. Recent work on simultaneous sintering of multiple alumina samples by Katz and Blake (1991) indicate energy requirements of 4.8 KWh/Kg or 2.2 KWh/lb of alumina, whereas Patterson et al. (1990) report a value of 3.8 KWh/Kg for alumina. In the latter case, net power consumption was reported rather than total power consumption -- i.e., the sum of input and reflected power. This study adopts the energy requirement values reported in Katz and Blake (1991) for alumina armor tiles.

No complete and reliable information was identified on the actual energy requirements for sintering silicon carbide material. Katz and Blake (1991) report that the power consumption required for the sintering of alumina-5 vol% silicon carbide composites is lower than for the sintering of 100% alumina because of the improvement in microwave coupling resulting from the addition of silicon carbide. The skin depth for lossy materials, such as silicon carbide, is on the order of microns; therefore, microwaves can easily be absorbed in those materials. However, due to a lack of sufficient information, the energy requirements for sintering silicon-carbide armor tiles are assumed to be identical to the energy required to sinter alumina armor tiles. This assumption should be updated as more information becomes available.

The total energy required during sintering depends on the dielectric loss factor of the material. The higher the dielectric loss factor of a material, the better will be the coupling with microwave energy. The overall engineering efficiency of microwave energy transfer varies from 50% to 60% -- i.e., "plug-to-product" -- which is comparable to the efficiency of conventional electric resistance furnaces. Although the efficiency of microwave energy transfer to the workpiece is more than 90%, the overall efficiency level reflects a 50% conversion efficiency of incoming electrical energy to microwave energy.

A reduction in overall efficiency of microwave energy occurs with an increase in frequency. Therefore, the model assumes firing heat efficiencies of 60% and 50% for 2.45 GHz and 28 GHz microwave power sources, respectively (Sanio and Schmidt, 1988). The energy cost of sintering a tile is calculated as the product of tile weight, electricity cost per KWh ($0.08/KWh in the base case), and the reciprocal of the firing heat efficiency and sintering yield factors.

4.2.2 Materials

Materials at the sintering step include insulation, tube replacement, and inert gas atmosphere. Two materials for armor tiles are considered in the model, i.e., alumina and silicon carbide. Depending on which material is selected, the model uses an appropriate density value in calculating tile weight. Note, however, that powder is not a material input or material cost at the sintering step. In a process-cost framework, powder enters as a material cost in the materials preparation step. Powder costs are not appropriately included in the cost of microwave sintering. Thus, the cost of process materials at the sintering step includes those material costs incurred during sintering of the tile, but not the cost of the ceramic material itself.

4.2.2.1 Insulation

For microwave sintering of alumina tiles, alumina bubbles with a density of 0.3 gm/cc at a cost of $4/lb (Jim Lee, Ceramic Fillers, Atlanta, GA) are assumed to be the insulating material. For silicon-carbide armor tiles, a mixture with a density of 1 gm/cc, consisting of 75 wt% boron nitride powder (at a cost of $50/lb, Union Carbide Corp., Cleveland, OH) and 25 wt% splintered granules of glassy carbon (at a cost of $115/lb, Lee Young, SIGRI Corp., Union, NJ) is assumed. The cost of the insulating material for silicon carbide armor tiles is therefore estimated to be $66/lb. The amount of insulating materials (in lbs) required per tile (I) is calculated as:

$$I = \frac{\text{Part Volume (cc)} * 5 * \text{Density of Insulating Material (gm/cc)} * \text{Waste Factor}}{\text{Sintering Yield} * 453.6}$$

A factor of 5 in the above formula indicates that insulation requirements equal 5 times the volume of the part being insulated. The densities of insulating materials are assumed to be 0.3 gms/cc and 1.0 gms/cc for alumina and silicon carbide tiles, respectively. The waste factor in the above formula indicates the fraction of insulating material actually lost (i.e., which cannot be reused) during the sintering process. The waste factor in the case of silicon carbide tiles, as well as alumina tiles, is assumed to be 0.05. The number 453.6 is required to convert grams to pounds.

4.2.2.2 Tube Replacement

Tube replacement cost for 2.45 GHz microwave power sources is estimated to be $1/W (according to Bob Alper, Varian Inc., Palo Alto, California). The average life of these tubes is about 50,000 hours; thus, tube replacement cost for a 2.45 GHz microwave power source is 2 cents/KWh. In the case of a 28 GHz microwave power source, tube replacement cost is estimated to be 5 cents/KWh (according to Bob Alper of Varian Inc.) A 200 KW cw magnetron costs about $350,000 with a life of approximately 35,000 hours. Note that the tube replacement costs calculated here fall in the lower range of estimates reported by Sanio and Schmidt (1988). Their estimated tube replacement cost is in the range of 1-12 cents/KWh. Tube replacement cost per tile is calculated as the product of energy required to sinter a tile and tube replacement cost per KWh and reciprocal of the sintering yield.

4.2.2.3 Inert Gas Atmosphere

The cost of the inert gas atmosphere (assumed to be argon) is estimated to be $0.30/cu.ft (Allied Chemicals, Knoxville, TN). The volume of inert gas atmosphere (in cubic feet) required per tile is calculated as the product of part volume, reciprocal of sintering yield, and the packing density factor.

4.2.3 Labor

Direct labor, calculated in terms of man-hours/day, is based on the total power of the microwave system required to attain the desired annual production volume. It is assumed that for the first 50KW microwave system, 1.5 persons (including both the operator and the materials handling personnel) are required; and for each additional 50KW microwave system, an additional 0.5 person is necessary. Thus, the quantity of direct labor, measured in man hours per day, is estimated by using the following equation:

$$\text{Direct Labor} = \text{No. of Shifts/Day} * \text{No. of Hours/Shift} * \left(1.5 + \frac{\text{Total Power of Microwave System (KW)} - 50}{50} * 0.5\right)$$

Direct labor cost is defined in ($/hour), is taken as an average rate for the industry, but may vary with geographical location or skill. Total labor costs are defined to include benefits and indirect labor costs. Employee benefits, such as vacation, retirement, insurance, and workmen's compensation are assumed to be 40% of direct labor rates (McNelis, Crawford, and Schmidt (1985)). Indirect labor (i.e., management personnel, secretaries, etc.) is assumed to be an additional 30% of direct labor rates.

The cost of direct labor per tile ($/part) is calculated by dividing the product of direct labor (man-hours/day) and labor rate ($/hr), by daily production volume (i.e., annual production volume/operating days per year). Labor overhead is estimated as 70% of direct labor cost, calculated as discussed above.

4.2.4 Capital

Capital costs include the costs of the microwave system and the materials handling equipment. Equipment costs are calculated based on annual production volume. The capital costs of a typical microwave system consist of five components: the generator, the applicator, power transmission equipment, instrumentation and controls, and installation and commissioning. Recent work by Sanio and Schmidt (1989) indicates that the generator represents less than 50% of the capital cost and the applicator and the remainder of the components represents greater than 50%. Sanio and Schmidt have estimated the capital and operating costs of a variety of dielectric heating systems (e.g., 915 MHz and 2.45 GHz) from a detailed engineering description. The total capital costs of alternative microwave systems were estimated to be between $1000 and $5000/KW and are within the range of earlier estimates by Smith (1984) and Wilson (1987). This study assumes that the capital costs of a 2.45 GHz microwave systems is $3000/KW, considering the probability that the cost of microwave equipment will decrease once microwave sintering technology is widely adopted. The need for gyrotrons rather than klystrons in the case of 28 GHz microwave power sources causes the capital cost of these microwave power sources to be significantly higher than for 2.45 GHz microwave power

sources. We assume that capital costs in this case will be $4000/KW, thus higher than the cost of 2.45 GHz microwave power sources. The total capital costs for a given annual rate of production volume in lbs/hr (V) (defined in Sect. 4.1) is calculated as:

$$\text{Total Capital Cost}(\$) = 3000 * V * \text{Energy Required for Sintering a Part}(\text{KWh/lb})$$

for a 2.45 GHz system, and

$$\text{Total Capital Cost}(\$) = 4000 * V * \text{Energy Required for Sintering a Part}(\text{KWh/lb})$$

for a 28 GHz system.

A 200 KW 28 GHz microwave system is currently estimated to cost $760,000 (source: Ross Faulkner, Continental Electronics Corporation, Dallas, TX). The cost per unit of KW thus calculated is comparable to the value being assumed here. The capital cost of materials handling equipment is assumed to be 10% of the total cost of the microwave system (source: Ray Paricio, Coors Ceramics Co., Golden, CO).

Capital charges are calculated as the yearly cost of capital, divided by the yearly production volume, where the cost of capital is based on the total cost of equipment assuming the given rate of interest. Capital charges are calculated as follows:

$$\text{Capital Charges}(\$/\text{part}) = \frac{(\text{Total Capital Costs} * \text{Cost of Capital})/(1-(1+\text{Cost of Capital})^{-n})}{\text{Yearly Production Volume}}$$

where n is equal to the number of years to recover the investment. The above equation assumes that the capital necessary to purchase the equipment is borrowed at a given rate and is repaid over a given number of time periods.

4.2.5 Other

"Other" includes capital maintenance, taxes and insurance, and building costs. Property taxes are based on the equipment owned and are calculated as a percentage of the purchase price and spread over the yearly production volume. The yearly tax burden is assumed to be 1.2% of the total equipment investment (main equipment, auxiliaries, and installation)(Poggiali, 1985). Note that this is a property tax, not a tax on net revenues. Similarly, yearly insurance is treated as a function of equipment cost and is calculated at 1 percent of total equipment investment. Yearly general maintenance costs are assumed to be 10% of the initial capital selling price (Sanio and Schmidt, 1988).

The last factor considered in the "Other" category is building cost, defined in terms of $/sq. ft/month. Building costs on a per-tile basis are calculated by dividing the product of total area required (sq. ft), building cost ($/sq.ft/month), and total number of months per year (i.e., 12) by annual production volume. To calculate the total area required for a given annual production volume, it is assumed that for the first 50KW unit of a 2.45 GHz microwave system, 400 sq. ft. of area are required; and for each additional 50KW microwave system, an additional 200 sq. ft. of area are

necessary. The corresponding values for a 28 GHz microwave system are 500 sq. ft. and 300 sq. ft., respectively (Bigelow, 1992). The larger area requirements for the 28 GHz microwave system are due to the use of gyrotrons. Thus, total area required for a given annual production volume using a 2.45 GHz microwave system is calculated as:

$$\text{Total Area (sq. ft.)} = 400 + \frac{\text{Total Power of Microwave System (KW)} - 50}{50} * 200$$

The total area for a 28 GHz system is calculated as:

$$\text{Total Area (sq. ft)} = 500 + \frac{\text{Total Power of Microwave System (KW)} - 50}{50} * 300$$

Building costs are assumed to be $0.20/sq. ft./month (McNelis, Crawford, and Schmidt, 1985).

4.2.6 Total Estimated Cost of Ceramic Armor Tiles

As discussed above, the total cost of the microwave sintering step is calculated as the sum of five major cost elements (i.e., materials, energy, labor, capital charges, and other). For the purposes of this initial analysis, the costs of pre- and post-sintering production steps are assumed to be identical to the costs of non-sintering steps when conventional sintering is used. For conventionally sintered tiles, the total cost of non-sintering steps has been estimated at 87% and 55% of the total cost for alumina and silicon carbide, respectively. Non-sintering costs for silicon carbide tiles are lower (in percentage terms) than for alumina tiles because in the former case uniaxial hot pressing contributes to a higher sintering cost. (Large periodic kilns are used for sintering of alumina tiles). The total costs of conventionally sintered alumina and silicon carbide tiles are assumed to be $7/lb and $50/lb, respectively (Ray Paricio, Coors Ceramics Co., Golden, CO and Rich Palicka, Cercom, Inc., Vista, CA). The total cost of a microwave sintered tile is estimated by adding the estimated cost of microwave sintering (derived from our process-cost model) to the estimated non-sintering costs of manufacturing conventionally-sintered armor tiles.

Table 1 provides output from the process-cost model. More specifically, the figure lists the assumed factor prices used in the analysis -- e.g., the per unit cost of energy, materials, labor, capital, insurance, and maintenance -- and the densities of the materials from which tiles are manufactured. Input factors are also listed in Table 1, including inputs such as part specification, operating time, production rate, sintering yield, sintering cycle time, and various sintering firing parameters.

Table 1. Factor prices and input factors

A	A	B	C	D
1	MICROWAVE SINTERING MODEL			
2	CERAMIC ARMOR TILES			
3				
4				
5	FACTOR PRICES			
6	==========			
7		units	$/unit	
8		----------	----------	
9	==========> ENERGY			
10	Electricity	Kwh*	0.08	
11				
12				
13		Density	gm/cu.cm	
14	==========> MATERIALS	----------	----------	
15	CHOOSE MATERIAL BY NUMBER =====>	1	3.97	
16	1. Alumina Standard Powder	gm/cu.cm	3.97	
17	2. Silicon Carbide Powder	gm/cu.cm	3.17	
18				
19				
20	Insulation	$/lb	$4.00	
21	Inert Gas Atmosphere	$/cu.ft	$0.30	
22				
23				
24	==========> OTHERS			
25	Direct Labor ($/man-hour)		$16.00	
26	Benefits (% of Direct Labor)		40%	
27	Indirect Labor (% of Direct Labor)		30%	
28				
29	Cost of Capital (% of initial investment)		12.0%	
30	Tax Burden + Insurance (% of physical plant)		2.2%	
31	Maintenance (% of physical plant)		10.0%	
32	Years to Recover Investment		10	
33	Building Cost	$/sqft/mo	$0.20	
34				
35				
36	INPUT FACTORS			
37	==========			
38	Plant Capacity (pieces/yr)		50000	
39	Part Length	cm	15	
40	Part Width	cm	15	
41	Part Thickness	cm	3	
42	Part Volume	cu. cm	675	
43	Part Weight	lbs	5.9	
44				
45				
46	Operating Time	days/yr	250	
47	No. of Shifts/Day		1	
48	No. of Hrs/Shift		8	
49	Production Rate	lb/hr	166	
50	Sintering Yield		90%	
51	Sintering Cycle Time	hrs	4	
52				
53				
54	CHOOSE FIRING METHOD =====>		1	
55				
56	1. Microwave 2.45 GHz			
57	2. Microwave 28 GHz			
58				
59				
60	MICROWAVE FURNACE PARAMETERS			
61				
62	Furnace Rating	KW	50	
63	Packing Density (Furnace Vol./Part Vol.)		25	
64				
65				
66	FIRING PARAMETERS			
67				
68	Microwave Energy Reqd. (Kbtu/lb) Known (Y/N)	Y	2.2	
69	Power Required To Raise Temp.	KW	NA	
70	Time To Raise Temperature	hrs	NA	
71	Power Required At Holding Temperature	KW	NA	
72	Time At Holding Temp.	hrs	NA	
73	Power Required While Cooling Down	KW	NA	
74	Time For Cooling Down	hrs	NA	
75	Batch Weight Used For Sintering Cycle	lbs	NA	
76	Firing Heat Efficiency: 1. 2.45 GHz		60%	
77	2. 28 GHz		50%	

5. RESULTS

This section presents empirical results from the microwave sintering model. The analysis conducted is divided into two parts -- (1) the selection of base-case parameter values and estimates of the cost of microwave sintering and total part cost when conventional and different microwave technologies are used; and (2) an assessment of the sensitivity of microwave sintering costs to changes in key economic and technical parameters.

5.1 BASE-CASE RESULTS

Table 2 lists the major base-case assumptions used in this analysis. The size of the tile is assumed to be the same for both materials, i.e., alumina and silicon carbide. Microwave power sources of two different frequencies (i.e., 2.45 and 28 GHz) are considered.

Table 2. Base-case assumptions for the microwave sintering step

Material	Alumina and Silicon Carbide
Part Size	150 x 150 x 30 mm
Part Weight	5.9 lbs (alumina)
	4.7 lbs (silicon carbide)
Annual Production Volume	50,000 parts
Sintering Yield	90%
Firing Heat Efficiency	
2.45 GHz	60%
28 GHz	50%
Labor Cost	$16/hr
Microwave Energy Reqd.	2.2 KWh/lb
Cost of Capital ($/KW) (excluding materials handling and building costs)	
2.45 GHz	3,000
28 GHz	4,000

Table 3 provides printout from the model, given our base-case assumptions for the case of alumina and a 2.45 GHz microwave system. The output provides estimated total units of factor inputs required to produce the base-case yearly production volume of 50,000 tiles. Also provided is the cost of each factor input on the basis of its contribution to total part cost ($/piece) and on the basis of $/lb. Toward the bottom of the table, information is provided on the distribution of costs by major cost category. Note that this cost distribution is for the sintering step only. The cost distribution is not reflective of the total cost of an armor tile.

At the bottom of the table is information on the estimated cost of an armor tile using microwave sintering and using conventional sintering. Note that, given our base-case assumptions,

Table 3. Summary model outputs

A	E	F	G	H	I
1	+----------				
2	MICROWAVE SINTERING				
3	+----------				
4					
5					
6	==========> EQUIPMENT	UNITS	$/UNIT	$/plant	
7					
8	McWave System (KW)	357	$3,000	1.07E+06	
9	Materials Handling Equipment	35.7	$3,000	$107,100	
10				=========	
11		Total ($/plant) =>		1.18E+06	
12					
13					
14					
15	==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
16					
17	Tube	14	$0.02	$0.29	$0.05
18	Insulation	0.12	$4.00	$0.50	$0.08
19	Energy	23.8	$0.08	$1.90	$0.32
20	Inert Gas Atmosphere	0.7	$0.30	$0.20	$0.03
21				==========	==========
22		Total =>		$2.88	$0.49
23					
24	==========> OTHERS			$/piece	$/lb
25					
26	Direct Labor (man-hours/day)	36.6	$16.00	$2.92	$0.50
27	Labor Overhead (Indirect + Benefits)		70%	$2.05	$0.35
28	Capital Charges		12.0%	$4.17	$0.71
29	Taxes + Insurance		2.2%	$0.52	$0.09
30	Maintenance		10.0%	$2.36	$0.40
31	Building	1628	$0.20	$0.08	$0.01
32				==========	==========
33			Total =>	$12.09	$2.05
34					
35					
36	COST DISTRIBUTION		Percent	$/piece	$/lb
37					
38	Materials		7%	$0.98	$0.17
39	Energy		13%	$1.90	$0.32
40	Labor		33%	$4.97	$0.84
41	Capital Charges		28%	$4.17	$0.71
42	Other		20%	$2.95	$0.50
43					
44					
45	=========>COST OF MCWAVE SINTERING STEP		=>	$14.98	$2.54
46					
47	=========>COST OF NON-SINTERING STEPS		=>	$35.93	$6.09
48					
49	=========>COST OF CONVENTIONAL SINTERING STEP		=>	$5.37	$0.91
50					
51	=========>COST OF CONVENTIONAL SINTERED TILE		=>	$41.30	$7.00
52					
53	=========>COST OF MCWAVE SINTERED TILE		=>	$50.91	$8.63
54					

the total estimated cost of the microwave sintering step on a per tile basis is $14.98 per tile. Using the methodology discussed above, the estimated cost of pre- and post-sintering steps is $35.93 per tile. The cost of sintering a tile using conventional technology is estimated at $5.37 per tile, and the estimated cost of a conventionally-sintered tile is $41.30 per tile (Ray Paricio, Coors Ceramic Co., Golden, CO). Applying the methodology as described above, this study estimates that the total cost of a microwave-sintered armor tile made from alumina and using a 2.45 GHz microwave system will be $50.91 per tile. The adoption of microwave sintering is not, therefore, expected to lead to a drastic increase in the cost of armor tiles. (Note that Table 3 also provides the same information on the basis of $/lb. of tile weight).

Figure 1 gives the estimated base-case cost of the microwave sintering step and its distribution by major cost category for the given two ceramic materials and two frequencies of microwave power sources. As indicated in the figure, the base-case cost of the microwave sintering step for alumina tiles is estimated at $14.98/part and $18.17/part for the 2.45 GHz and 28 GHz microwave power sources, respectively -- compared to an estimated conventional sintering cost of $5.37/part. Higher capital costs and lower firing heat efficiency cause the cost of microwave sintering with a 28 GHz system to be $3.19/part higher than the cost of a 2.45 GHz system. The total cost of a microwave-sintered alumina tile is estimated to be $50.91 and $54.10 for the 2.45 GHz and 28 GHz microwave power sources, respectively. The costs of microwave-sintered alumina tiles are, therefore, estimated to be about 1.3 times higher than conventionally-sintered tiles.

The costs of sintering silicon-carbide armor tiles with microwave technology are estimated to be more than double the costs of sintering alumina armor tiles. The base-case cost of the microwave sintering step is estimated to be $39.11/part and $41.66/part using 2.45 GHz and 28 GHz microwave power sources, respectively. Materials, at more than 60% of total cost, are estimated to be the largest cost component in the microwave sintering of silicon-carbide tiles. The use of expensive insulating materials (i.e., a mixture of boron nitride and glassy carbon at $66/lb) contributes to this significantly higher materials cost. Labor costs are also quite large (as was the case with alumina tiles) and are estimated to contribute 10% to 11% of total cost. The total cost of a silicon-carbide microwave-sintered tile is estimated to be $168.83 and $171.38 using 2.45 GHz and 28 GHz microwave power sources, respectively. Currently, these tiles cost about $235/part, significantly higher than the cost estimated for microwave-sintered tiles. This large cost difference is due to an assumed higher conventional sintering cost (i.e., 45% of total cost or $106.14/part, according to Rich Policka, Cercom, Inc., Vista, CA). This estimate appears suspiciously high and merits additional investigation. In contrast, the cost of sintering alumina tiles using conventional technology contributes only about 13% to total cost.

5.2 SENSITIVITY ANALYSES

This subsection presents the results of several sensitivity analyses in which selected economic and technical parameters were varied to estimate the impacts of those variations on the costs of the microwave sintering step and on total part cost. Results of these sensitivity analyses provide insights into how variations in key base-case parameters might alter the competitiveness of microwave sintering. The key parameters considered are sintering yield, annual production volume, the cost of labor, energy requirements, and capital costs. Alumina is the only tile material considered in the sensitivity analyses, as the sensitivity of most key technical parameters are identical for both materials.

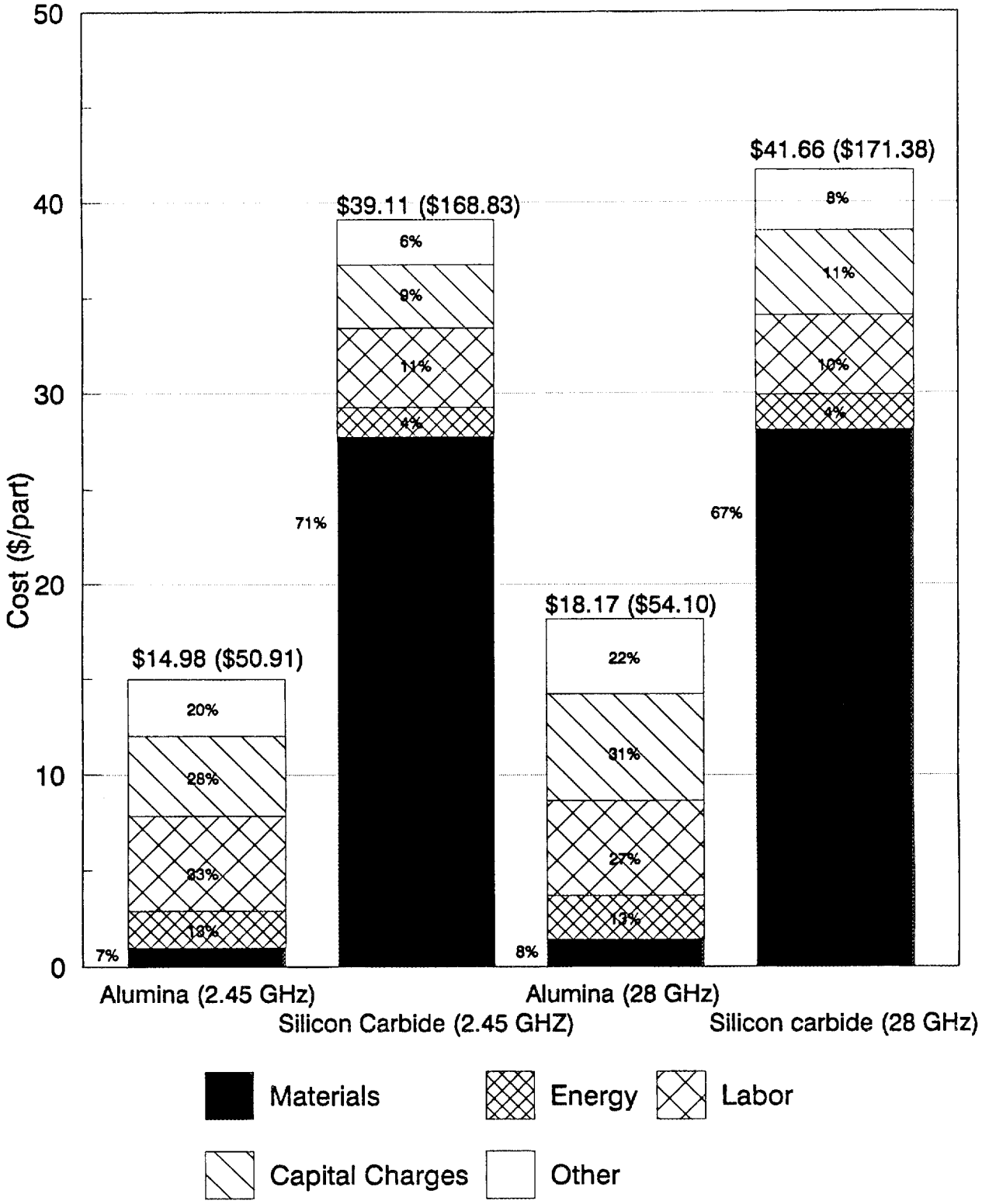

Fig. 1. Cost of the microwave sintering step
(Value inside the parenthesis indicates total part cost)

5.2.1 Sintering Yield

Figure 2 illustrates the estimated sensitivity of sintering costs and total part cost to changes in the yield at the sintering step. Note that the cost of production decreases monotonically for both microwave power sources when yield is increased. For example, an improvement in yield from 60% to 90% for both microwave power sources, results in the cost of sintering and total part cost to be reduced by about 30% and 12%, respectively.

5.2.2 Annual Production Volume

Figure 3 shows how cost is estimated to vary when annual production volume is changed. At low levels of production volume, cost is very sensitive to changes in output. The cost of the microwave sintering step decreases drastically, i.e., about $7.40/part for both microwave power sources, as production volume increases from 5,000 parts to 15,000 parts. The sensitivity of cost to production volume diminishes greatly as production volume increases to more than 50,000 parts. The cost of a microwave-sintered tile using 2.45 GHz microwave power technology could be as low as $50 for a production volume of more than 50,000 parts.

5.2.3 Labor Costs

The sensitivities of sintering cost and total part cost to changes in the labor rate ($/hr) for both microwave power sources are shown in Fig. 4. The cost of the microwave sintering step varies linearly -- i.e., a $0.47 per unit increase for each $1/hr increase in the labor rate. For a labor rate of $25/hr ($16/hr is assumed under the base-case), the cost of a 28 GHz microwave-sintered alumina tile is estimated to be $60.87.

5.2.4 Energy Required

As illustrated in Fig. 5, the cost of microwave sintering and total part cost are quite sensitive to changes in the microwave energy required during sintering. The microwave energy required (KWh/lb) is an input parameter and is assumed to remain constant with changes in production volume. This parameter is very important, as most costs including capital, energy, and labor are based directly on the quantity of energy required for sintering. The rating of a microwave system necessary for a given annual production volume depends on the microwave energy required; and labor costs depend on the number of microwave systems required to meet a specified annual production volume.

The cost of the microwave sintering step varies linearly with changes in energy requirements, i.e., $6.00/(KWh/lb) and $7.50/(KWh/lb) given 2.45 GHz and 28 GHz microwave power sources, respectively. As compared to a 2.45 GHz microwave power source, a 28 GHz system is more sensitive to changes in energy requirements because of the 28 Ghz system's lower firing heat efficiency and higher capital cost.

5.2.5 Capital Cost

Figure 6 illustrates the sensitivity of the costs of the microwave sintering step and total part cost to changes in capital cost ($/KW) for both microwave power sources. (Note that capital cost as defined here does not include the cost of materials handling equipment or building costs). The cost

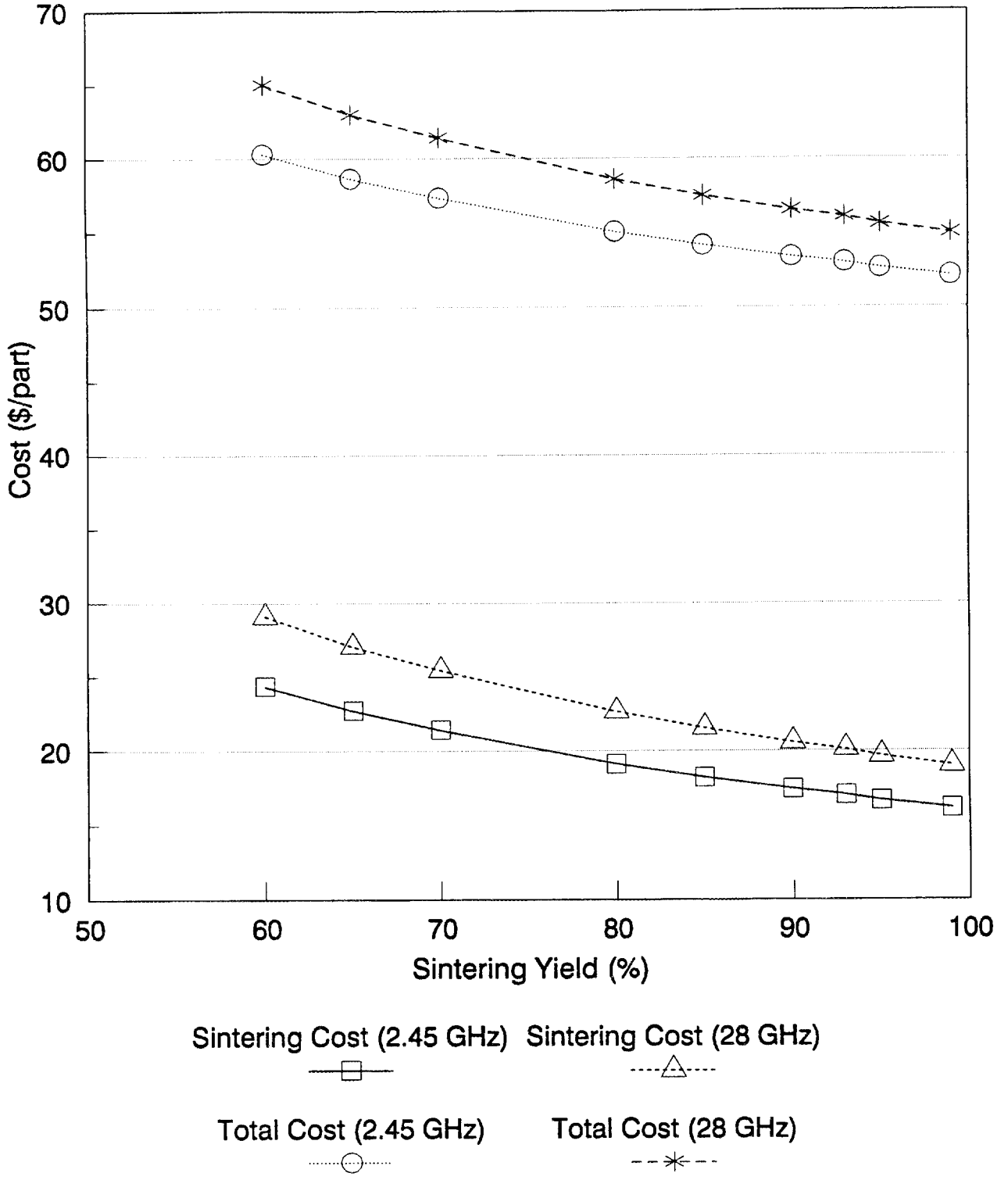

Fig. 2. Cost sensitivity to changes in sintering yield

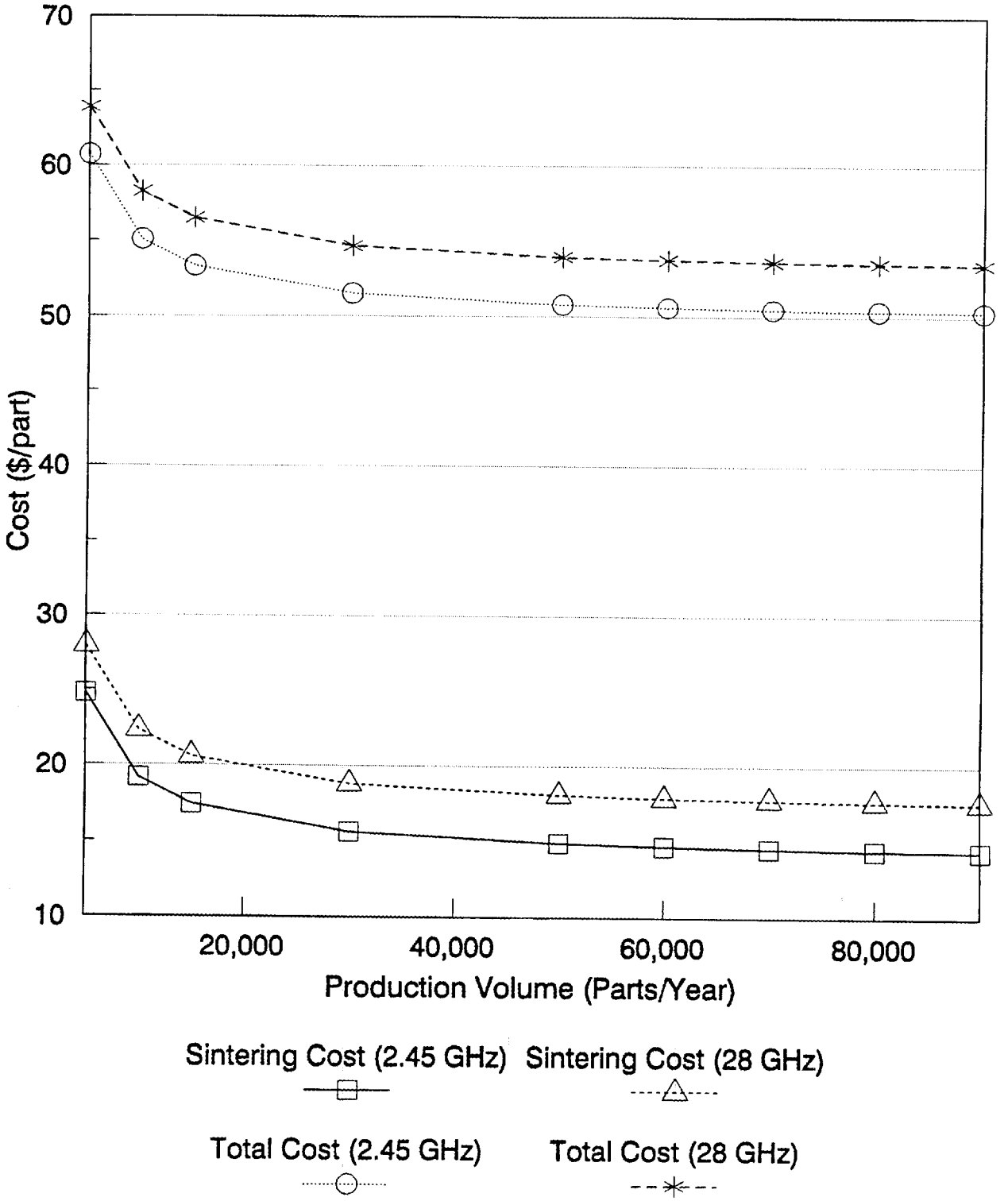

Fig. 3. Cost sensitivity to changes in annual production volume

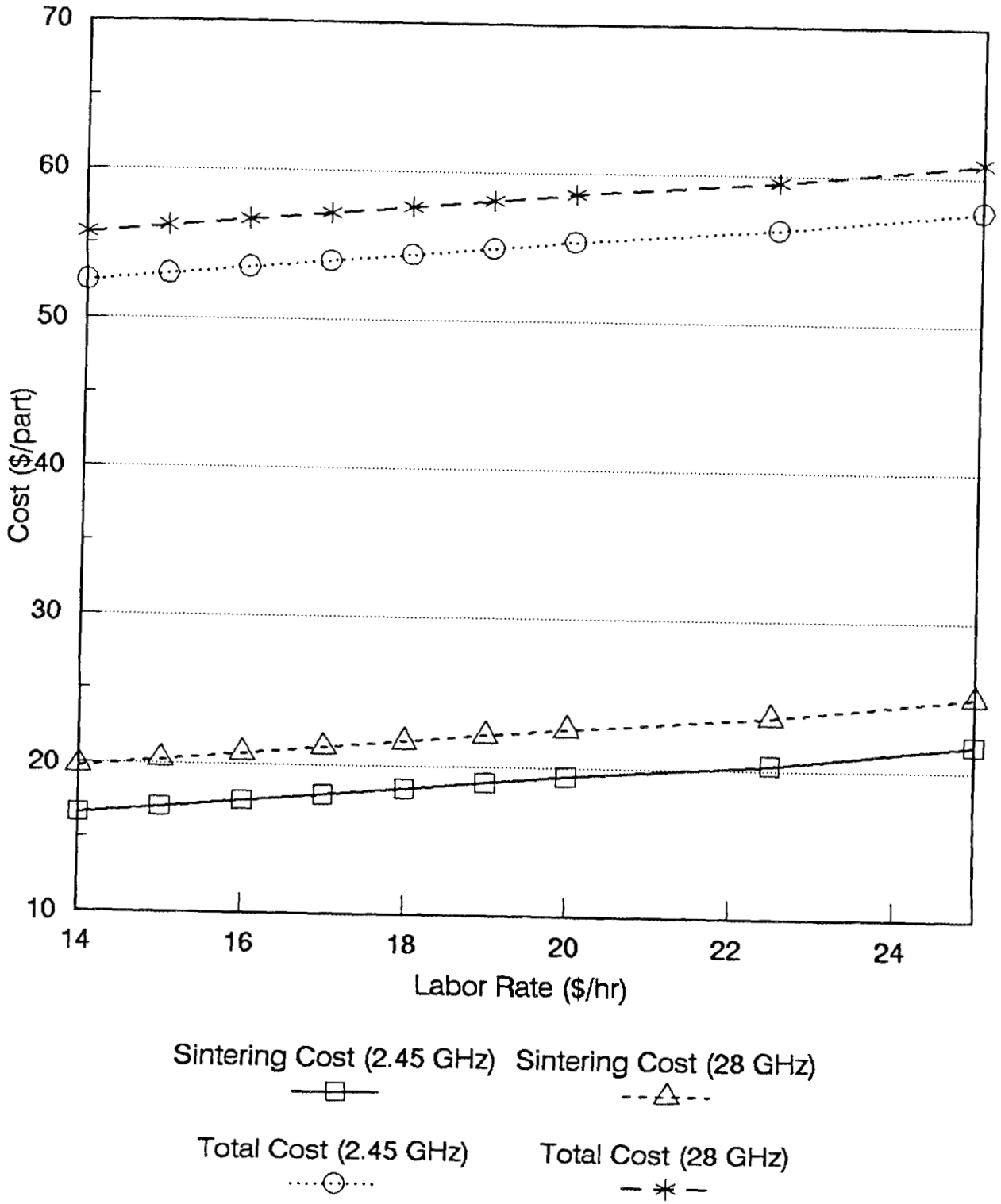

Fig. 4. Cost sensitivity to changes in labor rate

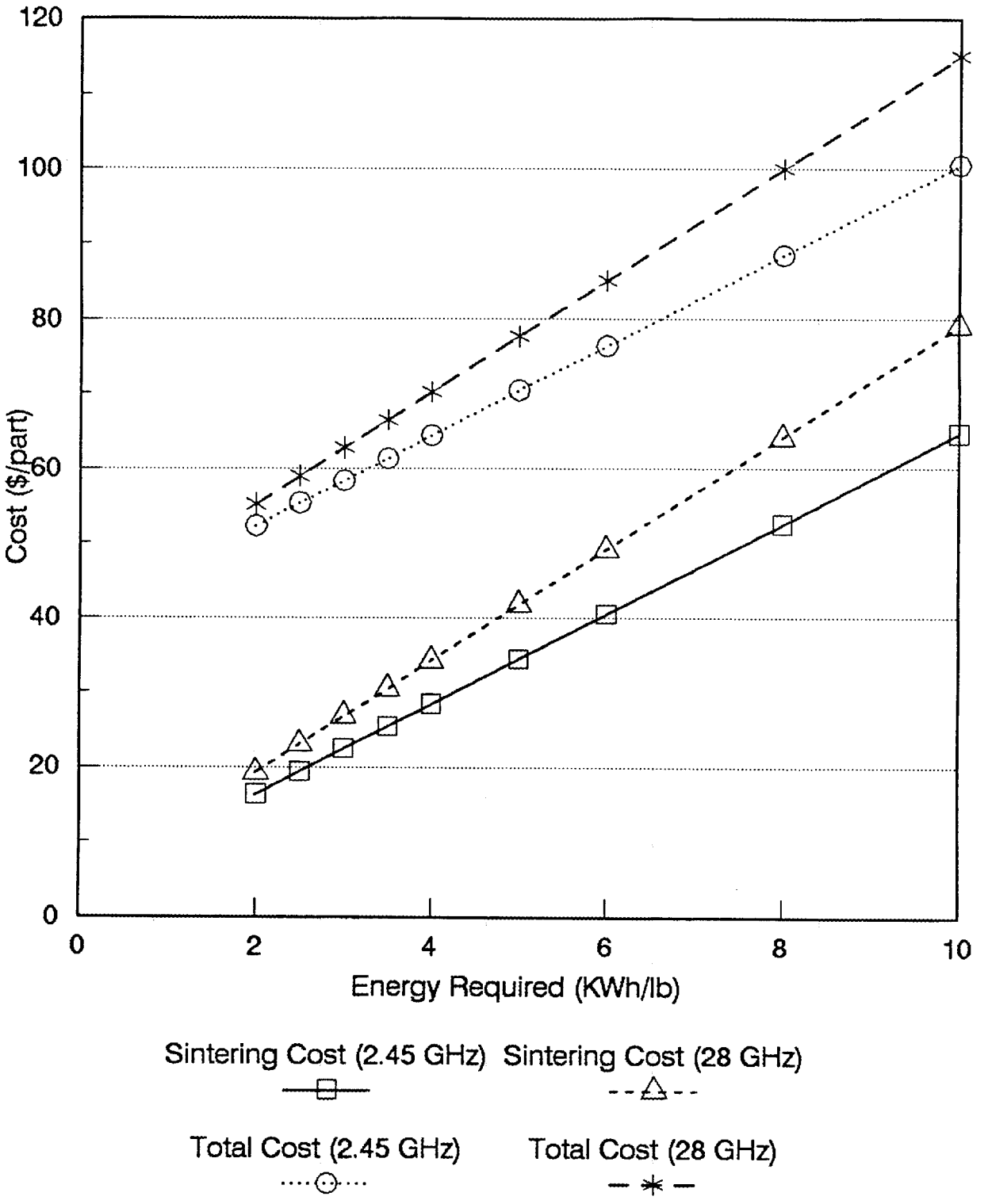

Fig. 5. Cost sensitivity to changes in energy required

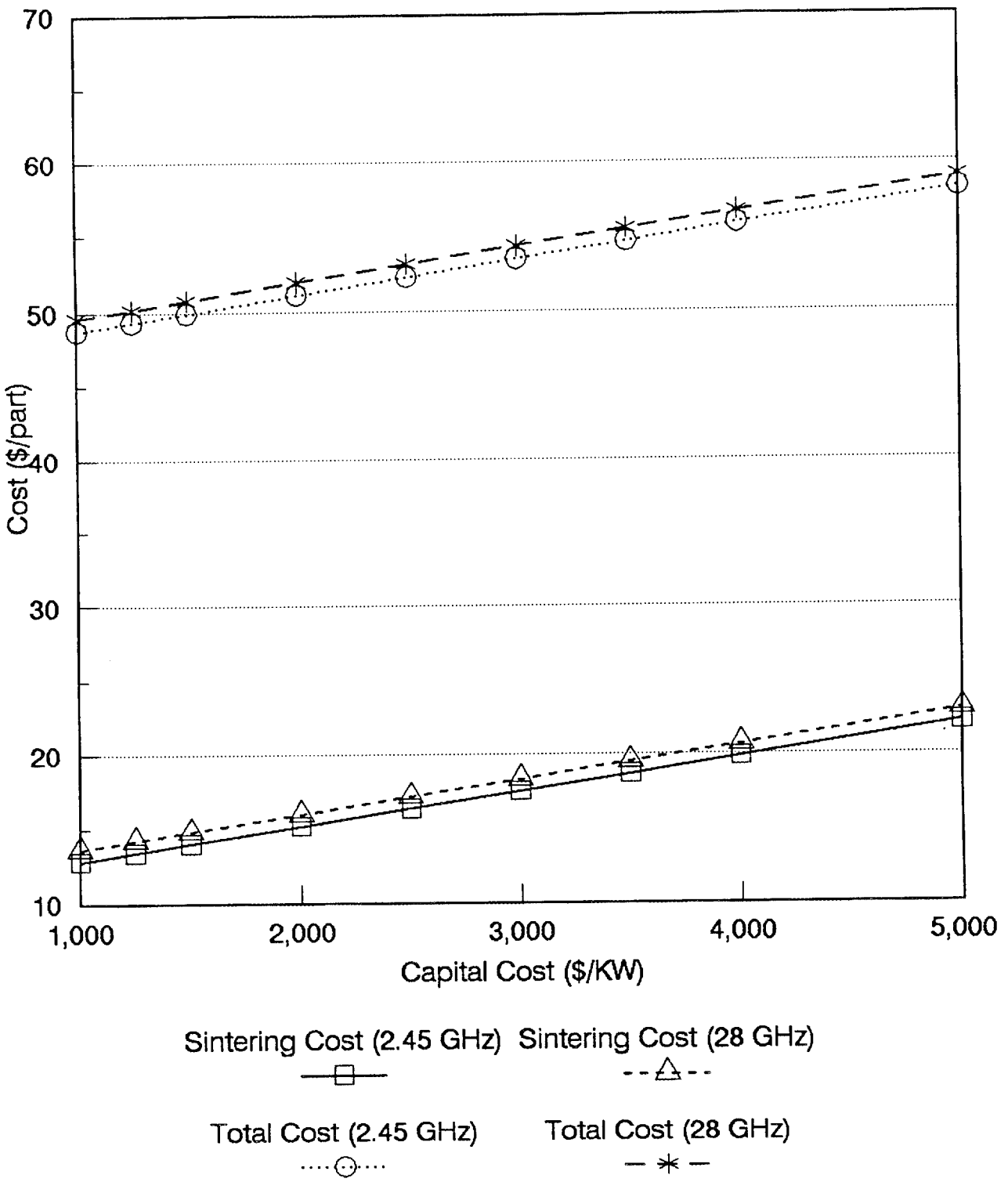

Fig. 6. Cost sensitivity to changes in capital cost

of microwave sintering and total part cost increase linearly with changes in capital cost -- i.e., $2.35 for a $1000/KW increase in capital cost.

6. CONCLUSIONS

This report documents the preliminary findings of a study to estimate the cost of manufacturing armor tiles using microwave sintering. The study considers two alternative microwave power sources -- 2.45 GHz and 28 GHz systems -- and two alternative ceramic materials -- alumina and silicon carbide. The model developed for this work focuses only on the cost of the sintering step. However, preliminary and rough estimates of the total cost of a microwave-sintered tile are also provided under the assumption that the costs of pre- and post-sintering steps in the production process will not be altered by the adoption of microwave sintering. This assumption is obviously flawed and will be dropped in the second phase of this work when the model is extended to include all pre- and post-sintering manufacturing steps. The model developed for this work utilizes a process-cost approach within a spreadsheet environment.

The base-case cost of sintering alumina tiles with microwave technology is estimated to be $14.98/part and $18.17/part, given the use of 2.45 GHz and 28 GHz microwave power sources, respectively. The higher sintering cost in the case of a 28 GHz microwave system results from the 28 GHz system's lower firing heat efficiency and higher capital cost as compared to a 2.45 GHz microwave power source. The cost of sintering alumina tiles with microwave technology is estimated to be more than three times that of conventional sintering. However, the adoption of microwave sintering is not expected to drastically increase the cost of ceramic tiles. More specifically, the cost of microwave-sintered alumina tiles is estimated to be about 1.3 times the cost of conventionally-sintered tiles.

In the case of silicon-carbide tiles, the base-case cost of microwave sintering is estimated to be lower than the cost of conventional sintering -- i.e., $39.11 and $41.66/part for 2.45 GHz and 28 GHz microwave power sources, respectively, as compared to a value of $106.14/part for conventional sintering). This study assumed that conventional sintering contributes 45% of the total cost of producing tiles (as compared to 13% in the case of alumina tiles). This assumption, which is based on information from industry experts, appears to be high and merits further analysis. The lower estimated cost of microwave sintering (in percentage terms) in the case of silicon carbide results in microwave-sintered tiles that are cheaper than conventionally-sintered silicon-carbide tiles (in the range of $170/part for the former case as compared to $235/part for the latter case).

Labor is estimated to be one of the largest cost components in the case of alumina tiles. The costs of capital charges, energy, other inputs, and materials follow in terms of their contributions to the cost of sintering alumina. The cost of ceramic powder is not taken into consideration at the sintering step. (Powder costs are incurred in the materials preparation step, which is yet to be modeled). Therefore, the cost of materials were not expected to be a major contributor to the cost of microwave sintering. However, this is not true in the case of silicon-carbide tiles because of expensive insulating materials. The expensive mixture of glassy carbon and boron nitride required for sintering silicon carbide -- at an assumed cost of $66/lb -- causes "materials" to be the largest cost component at the sintering step in the case of silicon carbide. Other than materials, the contributions of cost components to sintering cost follow the same order as was found in case of alumina tiles.

Several sensitivity analyses of changes in key economic and technical parameters on the costs of microwave sintering and total part cost were conducted. Those analyses indicate that costs are quite sensitive to changes in the quantity of microwave energy required during sintering. Energy

requirements are particularly important because they indirectly determine the quantities of labor and capital required for a given level of production volume. Patterson, Kimber, and Apte (1990) report that a significant improvement in energy efficiency can be achieved with an increase in the size of the load. Given the relative importance of energy inputs, further analysis of energy requirements and their impacts on cost is suggested.

The cost estimates discussed here are preliminary and should be updated as more technical information becomes available. In addition, the cost comparisons of microwave-sintered tiles with conventionally-sintered tiles should be interpreted carefully. The comparisons of total tile costs are made as the result of crude "back-of-the-envelope" calculations. Estimates of total tile costs remain incomplete without consideration of cost variations that occur in steps prior to and following the sintering step -- i.e., the subject of the next phase of this work. Finally, the economic viability of microwave-sintered tiles will not be determined by their cost alone, but rather on the balance of the marginal costs and benefits provided by microwave and conventional sintering technologies. To examine overall viability, further work is needed to evaluate the marginal costs and benefits of conventionally-sintered and microwave-sintered tiles.

REFERENCES

Alper, Bob (1992). personal communication, Varian Inc., Palo Alto, California.

Bigelow, T. S. (1992). personal communication, September 24, Fusion Energy Division, Y-12 Facility, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee.

Das, S. and T. R. Curlee (1988). "Ceramic Heat Exchangers: Cost Estimates Using a Process-Cost Approach," *Ceramic Bulletin*, vol. 67, no. 10, pp. 1684-89.

Das, S. and T. R. Curlee (1992). "The Cost of Silicon Nitride Powder and the Economic Viability of Advanced Ceramics," *Ceramic Bulletin*, vol. 71, no. 7, pp. 1103-11.

Faulkner, Ross (1992). personal communication, Continental Electronics Corporation, Dallas, Texas.

Katz, J. D. and R. D. Blake (1991). "Microwave Sintering of Multiple Alumina and Composite Components," *Ceramic Bulletin*, vol. 70, no. 8, pp. 1304-07.

Kimrey, H. D. and M. A. Janney (1988). "Design Principles for High-Frequency Microwave Cavities." *Microwave Processing of Materials*, Materials Research Society, Pittsburgh, PA, pp. 367-72.

Mingledorff, S. (1992). "A Methodology to Determine the Cost Competitiveness of Ceramic Materials with Current Tank Armor Technologies," U.S. Army Foreign Science and Technology Center, Department of the Army, Charlottesville, VA. Also a personal communication concerning the report.

McNelis, B. J., M. M. Crawford, and P. S. Schmidt (1985). "Energy Form-Value Models for Microwave and Conventional Heating Processes," Energy Productivity Project Report 85-3, Department of Mechanical Engineering and Center for Energy Studies, University of Texas, Austin, December.

Palicka, Rick (1992). personal communication, Cercom, Inc., Vista, California.

Paricio, Ray (1992). personal communication, Coors Ceramics Co., Golden Colorado.

Patterson, C. L., R. M. Kimber, and P. S. Apte (1990). "The Properties of Alumina Sintered in a 2.45-GHz Microwave Field," *Microwave Processing of Materials*, Materials Research Society, Pittsburgh, PA, pp. 1304-08.

Poggiali, B. (1985). "Production Cost Modeling: A Spreadsheet Methodology," M.S. Thesis in Materials Science and Technology, Massachusetts Institute of Technology, Cambridge, MA.

Sanio, M. R. and P. H. Schmidt (1988). "Economic Assessment of Microwave and Radio-Frequency Materials Processing." *Microwave Processing of Materials*, Materials Research Society, Pittsburgh, PA, pp. 337-346.

Schubring, N. W. (1983). "Microwave Sintering of Alumina Spark Plug Insulators," presented at the American Ceramic Society Electronics Division Fall Meeting, Grossinger, New York, Sept. 11-14, 1983.

Smith, R. D. (1984). "Microwave Power In Industry", EPRI Report EM-3645, Electric Power Research Institute, August.

Sutton, W. H. (1988). "Microwave Firing of High-Alumina Ceramics," *Microwave Processing of Materials*, Materials Research Society, Pittsburgh, PA, pp. 287-95.

Tinga, W. R. and W. A. G. Voss (1968). *Microwave Power Engineering*. Academic Press, New York.

Wilson, T. L. (1987). "Radio-Frequency Dielectric Heating In Industry," EPRI Report EM-4949, Electric Power Research Institute, March.

Young, Lee. (1992). personal communication. SIGRI Corporation, Union, New Jersey.

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