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An Assessment of the Cost of Microwave Sintering Ceramic Tiles for Armor Applications: Phase 2 Report

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MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
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AN ASSESSMENT OF THE COST OF MICROWAVE SINTERING CERAMIC TILES FOR ARMOR APPLICATIONS: PHASE 2 REPORT

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ABSTRACT

This report documents the findings of the second phase of work to assess the costs of microwave sintering ceramic tiles for armor applications. In the first phase of work, the cost of microwave sintering and preliminary estimates of the total cost of microwave-sintered tiles under two microwave frequencies (i.e., 2.45 GHz and 28 GHz) for alumina and silicon carbide materials were reported (Das and Curlee 1993). The second phase of work extends the previous work to include all pre- and post-sintering manufacturing steps and considers process and cost variations in these steps that may result from the adoption of microwave sintering. Two separate models were developed for two different materials. As before, a process-cost approach was utilized within a spreadsheet environment.

When compared to conventional sintering, the manufacturing of microwave-sintered alumina armor tiles will require an additional binder removal step prior to microwave sintering. The base-case cost of microwave-sintered alumina tiles is estimated to be $46.80/part and $50.50/part, given the use of 2.45 GHz and 28 GHz microwave power sources, respectively. The higher tile cost in the case of a 28 GHz microwave power source results from the unit's lower firing heat efficiency and higher capital cost, as compared to a 2.45 GHz unit. The estimated cost of microwave-sintered alumina tiles is in the range of $5.50 to $9.20 per part higher than conventionally-sintered tiles.

In the case of microwave sintering of silicon carbide armor tiles, the material preparation step will be significantly different from conventional sintering. Instead of a binder removal step, there will be a green machining step. The base-case cost of microwave-sintered silicon carbide tiles is estimated to be $324.50/part and $327.50/part for 2.45 GHz and 28 GHz microwave power sources, respectively -- compared to $235/part for conventionally-sintered tiles. The significantly higher powder cost for silicon carbide (i.e., $40/lb as compared to $2/lb for alumina) makes these tiles more expensive than alumina tiles.

The cost of materials is estimated to be the largest component in the total cost for both ceramic materials, i.e., 40% for alumina and 90% for silicon carbide. In the case of silicon carbide tiles, higher powder cost and expensive insulating materials necessary at the microwave sintering step are main contributors to materials cost. Most of the manufacturing cost, therefore, occurs at the material preparation step, followed by the sintering step. The firing step contributes 38% and 12.8%, respectively, to the total cost of microwave-sintered alumina and silicon carbide tiles.

Several sensitivity analyses of the impacts of variations in key economic and technical parameters on the costs of microwave-sintered tiles were conducted. Those analyses indicate that costs are quite sensitive to changes in the quantity of energy required during sintering. Since the changes at pre- and post-sintering steps are not envisioned to be significantly more expensive than similar steps for conventional sintering technology, the cost at the microwave sintering step will dictate the competitiveness of microwave-sintered tiles. Further analysis is suggested as more detailed technical information becomes available about all production steps.

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) is currently engaged in research for the U.S. Army Program Manager, Survivable Systems (PM-SS) 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. Assessment of the costs of microwave sintering armor tiles for armor applications has been done in two phases. The phase 1 work (i.e., Das and Curlee 1993) focused on estimating the costs of the microwave sintering step. The costs of microwave-sintered tiles were also estimated based on the assumption that all pre-sintering and post-sintering steps in the production of ceramic tiles are not altered by the adoption of microwave sintering. The cost of microwave-sintered alumina tiles were estimated in that report to be 1.3 times higher than the cost of conventionally-sintered tiles; on the contrary, about 1.4 times lower in the case of silicon carbide tiles. This report documents the second phase of work, which extended the analysis made in phase 1, to account for cost variations that may accompany the adoption of microwave sintering and occur in steps prior to and following the sintering step.

Ceramic armor materials have been used by the Army since the mid-1960s, and since the early 1980s the Army has been investigating the use of ceramics as components for land vehicle armor systems. Ceramic components are used primarily to defeat large-caliber (14.5 mm and greater) armor-piercing and kinetic energy (long rod) projectiles. Tungsten and silicon carbide armor materials have been shown to exhibit enhanced ballistic protective performance, particularly when the interface layers between ceramics and other encapsulating materials are properly designed. Alumina, silicon carbide, titanium boride, and aluminum nitride are some of the ceramic materials being considered for land vehicle armor systems. The most commonly used armor material is alumina. Armor tiles are currently being manufactured using the isopressing technology, followed by conventional sintering at a cost of $7/lb (Ghinazzi 1993). Silicon carbide armor material is used only in limited amounts. Either cold pressing followed by conventional sintering or hot pressing is used currently to manufacture silicon carbide tiles at a cost of $50/lb (Palicka 1992). The ongoing research at ORNL aims at improving the ballistic performance ranking of armor ceramics (specifically alumina and silicon carbide) by microwave sintering. Recent microwave postprocessing of alumina armor tiles by ORNL has shown 18% ballistic improvements. On a cost basis, it is difficult for ceramics (whether conventionally- or microwave-sintered) to be competitive with rolled, hardened steel armor materials currently in wide use by the Army, because of the significantly lower fabricated cost (i.e., $0.75/lb) of steel.

For this study, cost estimations of microwave-sintered tiles were made by expanding the microwave sintering model developed during phase 1 work. The expanded model includes the steps both prior to and following the sintering step. A separate cost model was developed for each tile material (i.e., alumina and silicon carbide), to reflect the unique process steps for the different materials. 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, depend not only on the cost differential between 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 that may be provided by improved ballistic performance.

2. APPROACH

This study's basic approach is to utilize the process-cost approach, in which a manufacturing technology is represented as a sequence of individual process steps. Poggiali (1985) provides a detailed description of the process-cost approach. In this study, process steps prior to and following the sintering step have been added to the original process-cost model, which modeled only the sintering step. Since in the process-cost approach, the output of the first process step -- in terms of total cost and the costs of individual inputs -- becomes an input to the second production step, and so forth, any positive or negative cost impacts that the adoption of microwave sintering will have on pre- and post-sintering steps can also be estimated. For each production step, 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 are estimated. An electronic spreadsheet modeling framework for these models provides flexibility in conducting sensitivity analyses with respect to key technology and cost parameters. The completed spreadsheet models are now available for further evaluation of economic variables as they become better known. In each case, 6"x6"x1.2" tiles were evaluated rather than tiles of a specific design for a specific tank armor.

3. MODEL DESCRIPTION

Two process-cost models were developed, each representing unique process steps for the two different armor materials. Pre- and post-sintering process steps are explicitly modeled. For the sintering process step, the microwave sintering step model developed during the phase 1 of this work is used; details are discussed in Das and Curlee (1993). Two microwave frequencies (i.e., 2.45 GHz and 28 GHz) are considered. Capital costs, energy requirements, firing heat efficiency, and other parameters at the microwave sintering step have been found to be sensitive to the frequency selected. However, due to a lack of information, values for the key technical and economic parameters assumed for the pre- and post-sintering steps in both the models are identical. The cost of materials handling equipment at each process step is assumed to be 10% of the capital cost. The process steps and their order assumed in these two models are illustrated in Fig. 3.1.

The following two sections discuss in detail various relationships between factor inputs and the production process for the pre- and post-sintering process steps used in the alumina and silicon carbide armor tile models; a complete listing of these models is included in Appendixes A and B, respectively. The major inputs to the process steps in process-cost models are materials, capital, energy, labor, and floor space; those inputs are discussed in detail, including data source(s) and functional relationships, by each process step in the following sections. Two other categories of input data -- factor prices and input factors assumed in these two models -- are given at the beginning of each appendix; in most cases, these are assumed to be similar to that in Das and Curlee (1993). Data on factor prices generally include data on the price of raw materials and energy, the labor rate, and the interest rate on borrowed capital. Production volume, part specification, process step yields, and other technical parameters are user-inputs, defined under the "input factors" category of data.

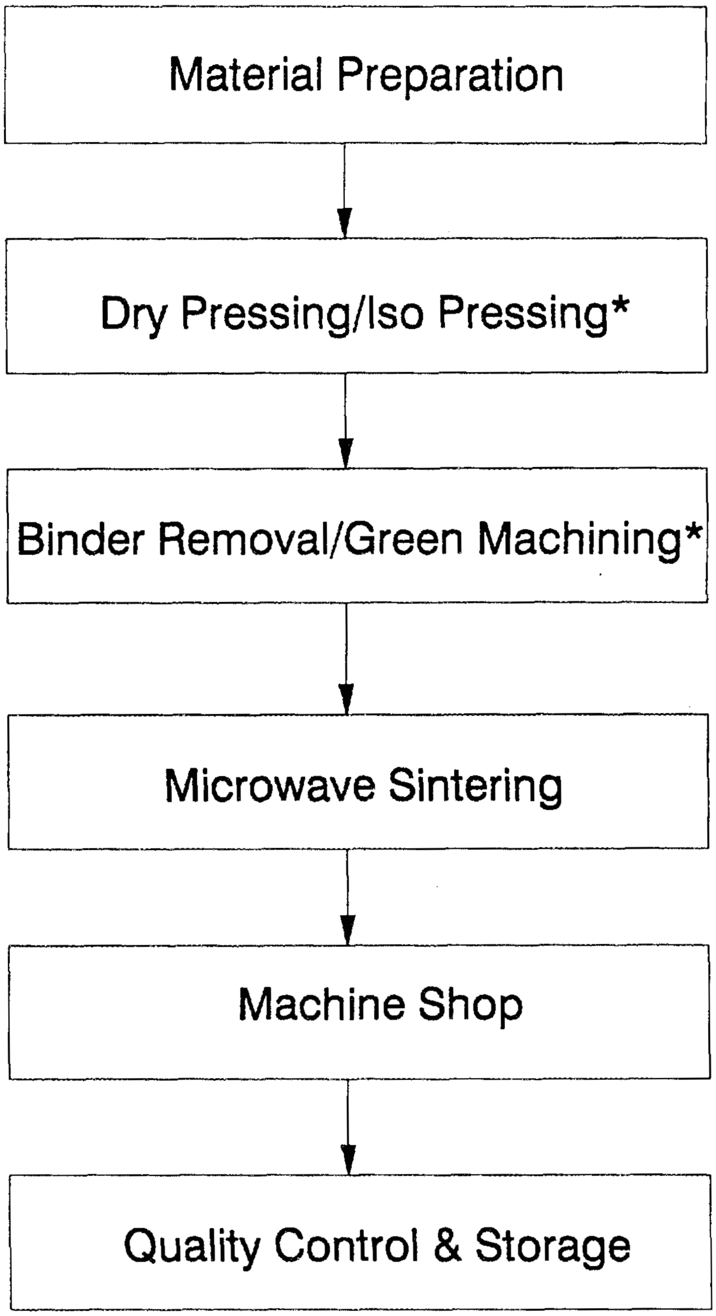

Fig. 3.1. Process steps in the process-cost models.

*Indicates that the process steps differ in the models for silicon carbide and alumina armor tiles

3.1 ALUMINA ARMOR TILES

The process-cost model developed for alumina armor tiles consists of six process steps, i.e., material preparation, dry pressing, binder removal, microwave sintering, machine shop, and quality control and storage. Binder removal is an additional step necessary in the case of microwave sintering in order to avoid contamination of the fired parts and furnace surfaces during sintering. The following sections discuss in detail the process steps and the input parameters and functional relationships used in each of these process steps.

3.1.1 Material Preparation

Material preparation is the first step in process-cost modeling. The material preparation step involves first ball-milling the alumina powder, followed by mixing of the powder with wax as the binder material in a slurry tank, and finally spray drying. The cost data for this step, obtained from Blanchard (1994), are based on a base-case production rate of 300 lbs/h. The capital cost of ball-milling and the slurry tank is assumed to be $120,000; for spray drying $150,000 is assumed. An additional 50% is added to the capital cost of spray drying to include the labor-intensive installation cost. The capital cost for any production rate is based on the assumption that a 10% change in a base-case production rate of 300 lbs/h will cause a 1% change in its corresponding capital cost value.

The cost of powder in this case also includes the cost of binder (i.e., containing 2 wt % wax), which is assumed to be $2/lb. The energy required for this process step includes (1) electricity for ball milling, pumps, etc., and (2) natural gas for spray drying. The amounts of electricity and natural gas required for a production volume of 300 lbs/h are assumed to be 200 kW and 2000 ft^3/h (equivalent to 2.224 MBtu/h), respectively. The amount of electricity (kWh) required per part (E) at this step is calculated as follows:

$$E = \frac{\textit{Total kW Rating (i.e., 200) x Part Weight (lbs)}}{\textit{Base Case Production Rate (i.e., 300 lbs/h) x Process Yield}^{1}}$$

In the case of natural gas, the value of 200 is replaced by 2.224. The labor cost is calculated similarly, assuming that 1.5 persons are required to run a material preparation facility at a production rate of 300 lbs/h. The labor (person-hours) required per part (L) at this step is calculated as follows:

$$L = \frac{1.5 \textit{ x Part Weight (lbs)}}{\textit{Base Case Production Rate (i.e., 300 lbs/h) x Process Yield}}$$

Finally, the amount of floor space required for this process step is assumed to be 2000 ft^2 for a production rate of 300 lb/hr. For each additional production increment of 300 lb/h, an additional 1000 ft^2 of area are necessary. The amount of floor space (A) required for this process step is thus calculated as follows:

$$A = 2000 + \left(\frac{\textit{Production Rate (lb/h)} - 300}{300} \right) x\ 1000$$

---

[1]Yield is defined as the physical yield of the process (i.e., 1-scrap rate)

3.1.2 Dry Pressing

After the material preparation step, the alumina powder is formed into the required shapes by dry pressing. Higher production rates and closer tolerances are achievable in dry pressing than in isostatic pressing. Most of the data for this step are obtained from Ghinazzi (1994). The capital cost at this step is assumed to be $750,000, on the basis of three machines with an output level of 500 parts per shift. (The number of machines at a unit cost of $250,000 is calculated on the basis of the required shift output). The cost of the mold for dry pressing is assumed to be $350, with a life of 2500 parts.

The amount of electricity required for dry pressing is calculated based on the assumption that each dry pressing machine requires 40 HP of electricity. The labor cost assumes that the first dry pressing unit requires 1 person; for each additional unit, an additional 0.5 person is necessary. The amount of floor space required for this step is based on the number of dry press units required, assuming that 500 ft^2 are needed per dry press unit.

3.1.3 Binder Removal

The binder removal step is a necessary step prior to microwave sintering. In conventional sintering of armor tiles, binder removal and sintering are done in a single step. In the case of microwave-sintered armor tiles, fouling of the microwave furnace during binder removal may necessitate an additional binder removal step. The binder removal step involves baking the armor tiles in a conventional furnace at 600°C for 4 h. Most of the data for this step are obtained from Gaudette (1994). It is assumed that a furnace of 90"L x 14"W x 2"H heating zone costs $40,000. The capital cost for this step is based on the number of such furnaces required to meet the required batch quantities (i.e., the number of tiles required to be processed per drying cycle to meet the required annual production volume). The number of furnaces (N) is calculated as follows:

$$N = \frac{Batch\ quantity\ x\ Tile\ size\ (inches^2)}{Furnace\ heating\ zone\ size\ (i.e.,\ 90x14)}$$

The energy calculations at this step are based on functional relationships used by the authors in energy calculations for the sintering step in an extrusion model for ceramic heat exchanger tubes (Das et al. 1988). This process step is the least labor-intensive and for most of the time is an unattended operation. The amount of labor required is assumed to be 0.5 person per shift. The total amount of floor space required at this step is assumed to be three times the size of the floor space required by the furnaces. Each furnace is assumed to require a floor space area of 52 ft^2.

3.1.4 Machine Shop

The machine shop process step includes the grinding operation on microwave-sintered tiles. The data for this process step are obtained from Ghinazzi (1993). Calculation of the capital cost for this process step for the required production rate is based on the assumption that three grinding machines (for a total cost of $75,000) can produce an output rate of 250 parts/shift. Grinding wheels required at this process step are assumed to be $400 each with a life of 500 parts.

The amount of electricity consumed in this process step is based on the assumption that a total 40 HP of electricity is necessary at this step. Assuming that 250 parts/h can be machined, the amount of electricity (E) in kWh consumed per part is

$$E = \frac{40 \times 0.746}{250 \times Process\ \ Yield}$$

Calculation of the amount of labor is based on the assumption that two persons are necessary to run a facility having three grinding machines. The amount of floor space required per machine is 100 ft^2 plus an additional 75 ft^2 for other accessories.

3.1.5 Quality Control and Storage

Quality control and storage is the last process step in the production of microwave-sintered armor tiles. It is also the least expensive step, as this process may entail only visual inspection for cracks and dimensional accuracy measurements for a random number of tiles. The capital cost for this process step is assumed to be $5,000 for an annual production volume of 25,000 parts. The manual nature of the process precludes any electricity consumption at this step. The amount of labor required is assumed to be 1 person with a production rate of 60 tiles/h and with inspection being done only on 10% of the total tiles manufactured. The amount of floor space required for an annual production volume of 25,000 parts is assumed to be 100 ft^2.

3.2 SILICON CARBIDE ARMOR TILES

The process-cost model developed for silicon carbide armor tiles consists of an identical number of process steps (i.e., six) as in the case of alumina armor tiles. The major difference in process steps between these two materials is at the forming step and the binder removal step. Cold isostatic pressing is assumed in the case of silicon carbide, as compared to dry pressing for alumina armor tiles. The binder removal step after the forming step used in the alumina tiles is replaced by the green machining step. The green machining step cuts the green silicon carbide blanks obtained at the isostatic step into the required shape and size. No binder removal step is necessary for silicon carbide tiles because the use of alcohol-based binders and a flowing inert atmosphere during microwave sintering prevents any contamination of the fired parts and the furnace surfaces.

Forrestor (1994) provides the major technical details for the processing of silicon carbide tiles. The following sections discuss in detail the process steps, the input parameters, and the functional relationships used in each of these process steps. Where the functional relationships are the same as those for alumina tiles, the discussion is not repeated. The material preparation, isostatic pressing, green machining, and machine shop process steps are discussed in the following paragraphs. The microwave sintering step has been discussed in Das and Curlee (1993), and the quality control and storage process step is identical to the one discussed earlier for alumina tiles.

3.2.1 Material Preparation

In the material preparation process step, silicon carbide powder containing Al_2O_3 + Y_2O_3 as the sintering aids is mixed with 1 wt % max. Klucel -- a kind of artificial sugar ($7.40/lb) and a mixture of 50% each of acetone ($30/L) and ethanol/methanol ($20/L). The ratio of the mixture of acetone and ethanol/methanol to the powder weight is 1:10. The cost of the powder mixture is assumed to be $40/lb, where the cost of binder is estimated to be less than $1/lb (currently, due to its proprietary composition, Cercom, Inc. sells the powder with sintering aids in small quantities at $100/lb). The powder mixture is mixed in jar mill mixers for 4 h (currently, a 6.6-gal. capacity mixer costs $2100). The labor per part at this step is calculated assuming that 0.25 person is necessary to run a mixer with a 6.6-gal capacity, having a mixing rate of 20 lb of powder per hour.

The silicon carbide powder containing sintering aids is first ball-milled, then mixed with binders in jar mill mixers, and finally dried and screened. The costs associated with the ball-milling operation are assumed to be identical to those for alumina tiles, as discussed earlier. The only other major cost to be estimated is for the screening operation (as the jar mill mixing operation has already been discussed above), for which most of the data were obtained from Ling (1994). The capital cost of screening for a given production volume is estimated based on an assumed cost of $12,000 for a 48-in.-diam. round separator with a screening capacity of 0.5 tons/h from the initial mesh size of +10 to -100 - +200 mesh size. The electricity consumed by such a single machine is 2.5 HP, and 0.25 person/machine is required for the operation. The amount of floor space required for screening is assumed to be 25 ft^2 for each machine.

3.2.2 Isostatic Pressing

Favastano (1994) and Sommer (1994) provided most of the technical data related to cost calculations for the isostatic pressing step. Calculation of the capital cost for this step is based on the assumption that a cold isostatic press (12" in diameter and 36" in height) costs $100,000 and that 4000 $in.^3$ (= 100 tile volumes) of powder can be pressed to a blank at a pressure of 30,000 psi for a total cycle time of 20 min. The capital cost and other cost calculations at this step are based on the number of such machines required for a given hourly production rate. The mold cost is assumed to be $20/piece with an estimated life of 10 blanks/mold. The energy calculations assume that a 20 HP/machine is required; the labor requirement for this process step is 1 person/machine (includes loading of the powder and unloading of the blank). The amount of floor space required per machine is assumed to be 50 ft^2.

3.2.3 Green Machining

In the green machining step, the ceramic blanks obtained after cold isopressing are cut into the required shape and size of armor tile using a band saw with diamond blade. The data for this process step are obtained from Ohnsorg (1994). The capital cost of a band saw with a self-contained dust collector system is assumed to be $20,000; the saw is capable of an hourly production rate of 20 pieces. The diamond wheel required for this process is estimated to cost $400/piece and have an average life of 200 tiles/wheel. The labor requirement for this process step is 1 person/machine. The energy required per machine is 2 HP, and a minimum floor space area of 20 ft^2 is required for each machine.

3.2.4 Machine Shop

In the case of silicon carbide tiles, diamond grinding is necessary to remove surface reaction layers as well as to obtain dimensional specifications. The data for this process step are obtained from Costello (1994). It is assumed here that a rotary surface grinder will be used. A capital investment of $120,000 will be necessary to produce an output rate of 6 parts per hour. Diamond wheels required at this process step are assumed to be $800 a piece, with a life of 1000 parts.

The amount of electricity consumed in this process step is based on the assumption that 20 HP of electricity is consumed to machine 6 tiles/hr. The amount of labor required is assumed to be 1 person running two grinding machines; the amount of floor space required is 100 ft^2 per machine.

4. RESULTS

This section presents empirical results from the two models. These results should be considered preliminary, since assumptions made with regard to key technical and economic parameters may change as more information is available about the technologies being considered. The analysis is divided into two parts: (1) the selection of base-case parameter values and estimates of the cost of microwave-sintered tiles; and (2) an assessment of the sensitivity of the tile cost to changes in key technical and economic parameters. The base-case parameter values reflect current or near-term state-of-the-art manufacturing processes. Results of the sensitivity analyses provide insights into how variations in key base-case parameters might alter the competitiveness of microwave sintering. In the sensitivity analyses, only a single parameter is changed at a time while other parameters remain at their base-case values. Note that conventionally-sintered alumina and silicon carbide tiles currently cost $41.30/part and $235/part, respectively.

4.1 ALUMINA ARMOR TILES

4.1.1 Base-Case Results

Table 4.1 lists the major base-case assumptions used in the cost estimation for microwave-sintered alumina tiles. As indicated, the cost of alumina powder is assumed to be $2/lb, and the total yield to be 72% in the base case.

Figure 4.1 gives the estimated base-case cost and its distribution by major cost categories for manufacturing microwave-sintered alumina tiles for the given two microwave frequencies. As indicated in the figure, the base-case cost of the tiles is estimated at $46.80/part and $50.50/part for the 2.45 GHz and 28 GHz microwave power sources, respectively -- compared to the cost of $41.30/part for conventionally-sintered tiles. Higher capital costs and lower firing heat efficiency cause the cost of microwave-sintered alumina tiles with a 28 GHz system to be $3.70/part higher than the cost of tiles with a 2.45 GHz system. Materials, at about 40% of total cost, are estimated to be the largest cost component of microwave-sintered alumina tiles, and powder cost contributes almost 90% of this materials cost. Labor and capital charges each contribute about 20% of the total cost.

In terms of processes, two steps -- material preparation and firing -- contribute more than 80% of the total cost for the 2.45 GHz system, as shown in Fig. 4.2. Powder cost is the main contributor to material preparation cost, whereas capital charges and labor constitute the major costs for the firing step. The only other significant cost occurs at the pressing step. Binder removal and inspection are the least expensive process steps. As noted in the earlier discussion, the binder removal step is the additional process step necessary in the case of microwave-sintered tiles; however it adds only $0.80/part to the total cost.

Table 4.1. Base-Case Assumptions for the Microwave Sintering of Alumina Tiles

Parameter	Assumption
Material	Alumina
Powder Cost	$2/lb (including binder)
Part Size	150 x 150 x 30 mm
Part Weight	5.9 lb
Annual Production Volume	50,000 parts
Process Step Yields*	
Material Preparation	98%
Dry Pressing	95%
Binder Removal	95%
Sintering	90%
Grinding	95%
Inspection	95%
Total	72%
Firing Heat Efficiency	
2.45 GHz	60%
28 GHz	50%
Labor Cost	$16/h
Microwave Energy Reqd.	2.2 kWh/lb
Cost of Capital ($/KW)	
2.45 GHz	3,000
28 GHz	4,000

*Yield is defined as the physical yield of the process (i.e., 1-scrap rate).

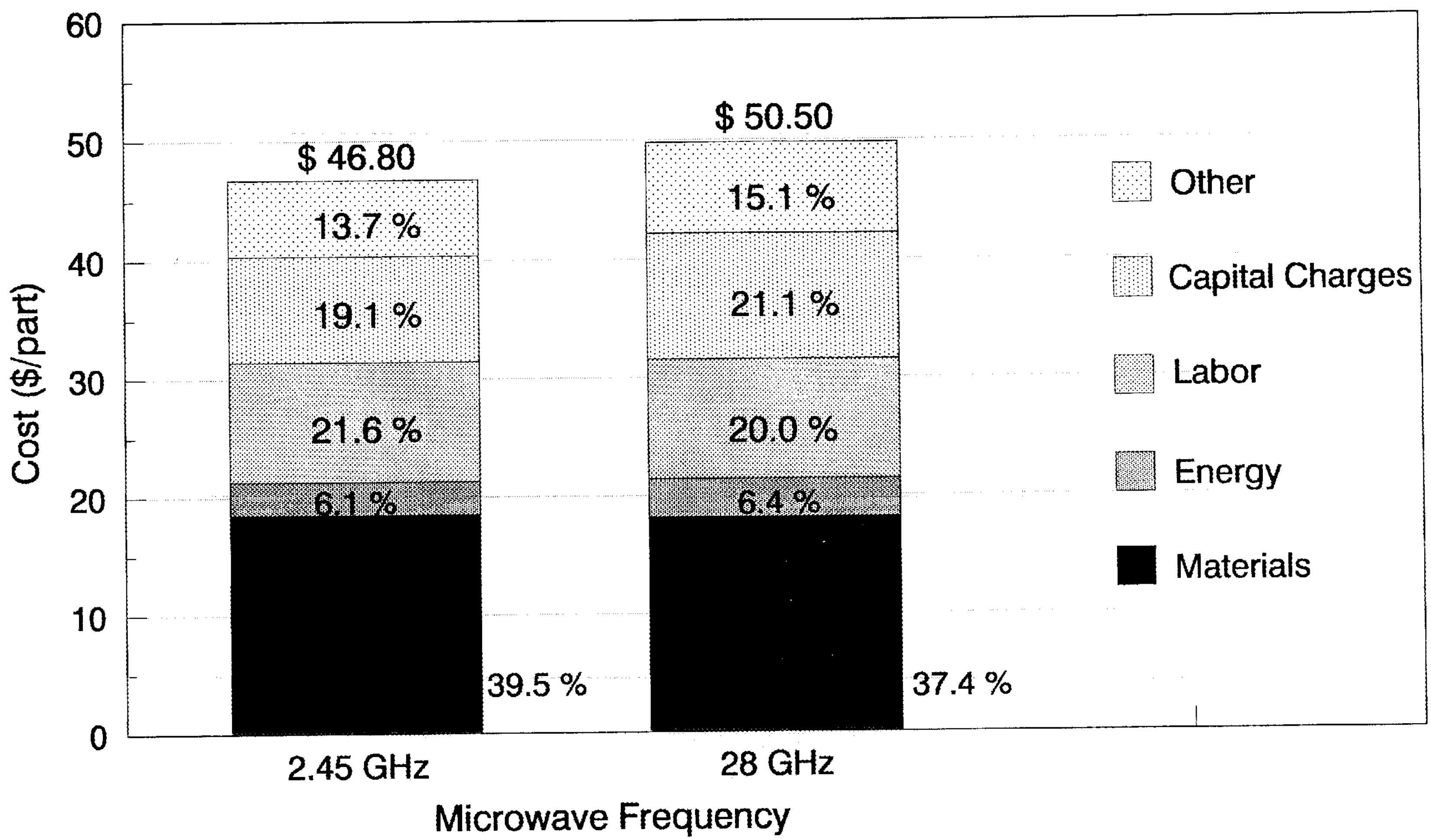

Fig. 4.1. The base-case cost of microwave-sintered alumina tiles.

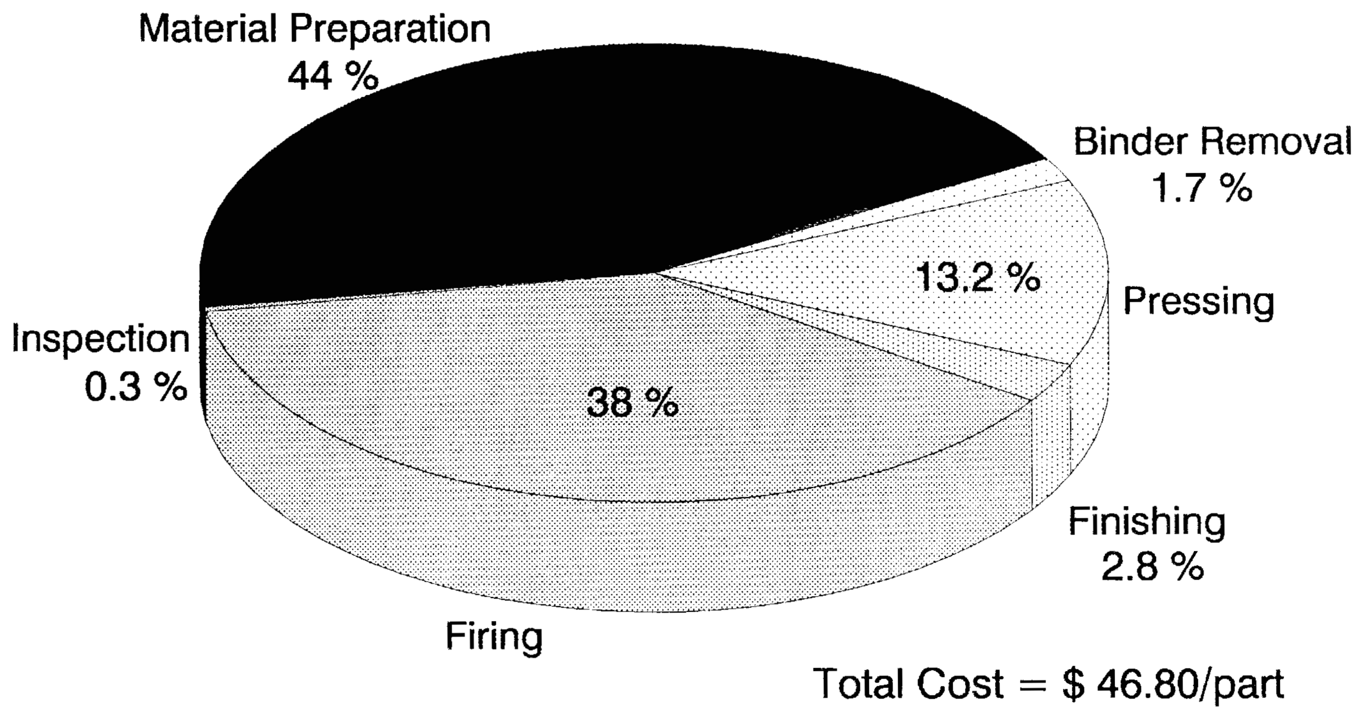

Fig 4.2. The base-case cost distribution of 2.45 GHz microwave-sintered alumina tile by process steps.

4.1.2 Sensitivity Analyses

Given that cost-reducing improvements are likely along several technology fronts, the process-cost model was used to estimate the technology parameters, to which total cost is most sensitive. Particular emphasis was given to the microwave sintering step about which technical details are little known. Sensitivity analysis was performed on several technical parameters, including annual production volume, sintering yield, and energy required at the sintering step.

4.1.2.1 Annual Production Volume

Figure 4.3 shows how tile cost is estimated to vary with annual production volume. The cost is very sensitive to annual production volume up to a value of less than 50,000 parts. The cost of a tile decreases by $6.30 as the annual production volume is increased from 15,000 parts to 60,000 parts. With an annual production greater than 60,000 parts, the tile cost is estimated to be about $46/part in the case of a 2.45 GHz system, about $5.50/part higher than the cost of a conventionally-sintered tile.

4.1.2.2 Sintering Yield

The sensitivities of tile costs to changes in sintering yield for both microwave power sources are shown in Fig. 4.4. Note that the cost of production decreases monotonically for both microwave power sources when yield is increased. For example, an improvement in yield from 90% (the base-case value) to 98% results in the cost of tile being reduced by about 8.5% and 8.4%, respectively. A sintering yield of 98% could bring down the cost difference between microwave- and conventionally-sintered tiles to $1.50/part.

4.1.2.3 Energy Required

Earlier analysis on the cost of the microwave sintering step (Das and Curlee 1993) indicated that the cost of microwave sintering is very sensitive to energy requirements at that step. Most costs -- including capital, energy, and labor at that step -- are based directly on the quantity of energy required for sintering. Figure 4.5 shows the sensitivity of tile cost to changes in energy required (kWh/lb) at the microwave sintering process step. Tile cost increases linearly [to $7.20/(kWh.lb) and $8.90/(kWh.lb)] for 2.45 GHz and 28 GHz microwave power sources, respectively. For example, in the case of a 2.45 GHz system, the tile cost triples if the energy required increases by 10 times. The tile would cost $40.00 ($1.30/tile less than the cost of a conventionally-sintered tile) for a 28 GHz system if the energy requirement could be reduced to 1 kWh/lb.

4.2 SILICON CARBIDE ARMOR TILES

4.2.1 Base-Case Results

The major base-case assumptions used in the cost estimation of microwave-sintered silicon carbide tiles are very similar to those in the case of alumina tiles (as discussed above) and are listed in Table 4.2. Models for the two materials differ in terms of part weight (due to the difference in density between the two ceramic materials) and powder cost. The cost of powder for silicon carbide tiles is assumed to be $40/lb, and the total yield and yearly production volume are assumed to be 72% and 50,000 parts, respectively.

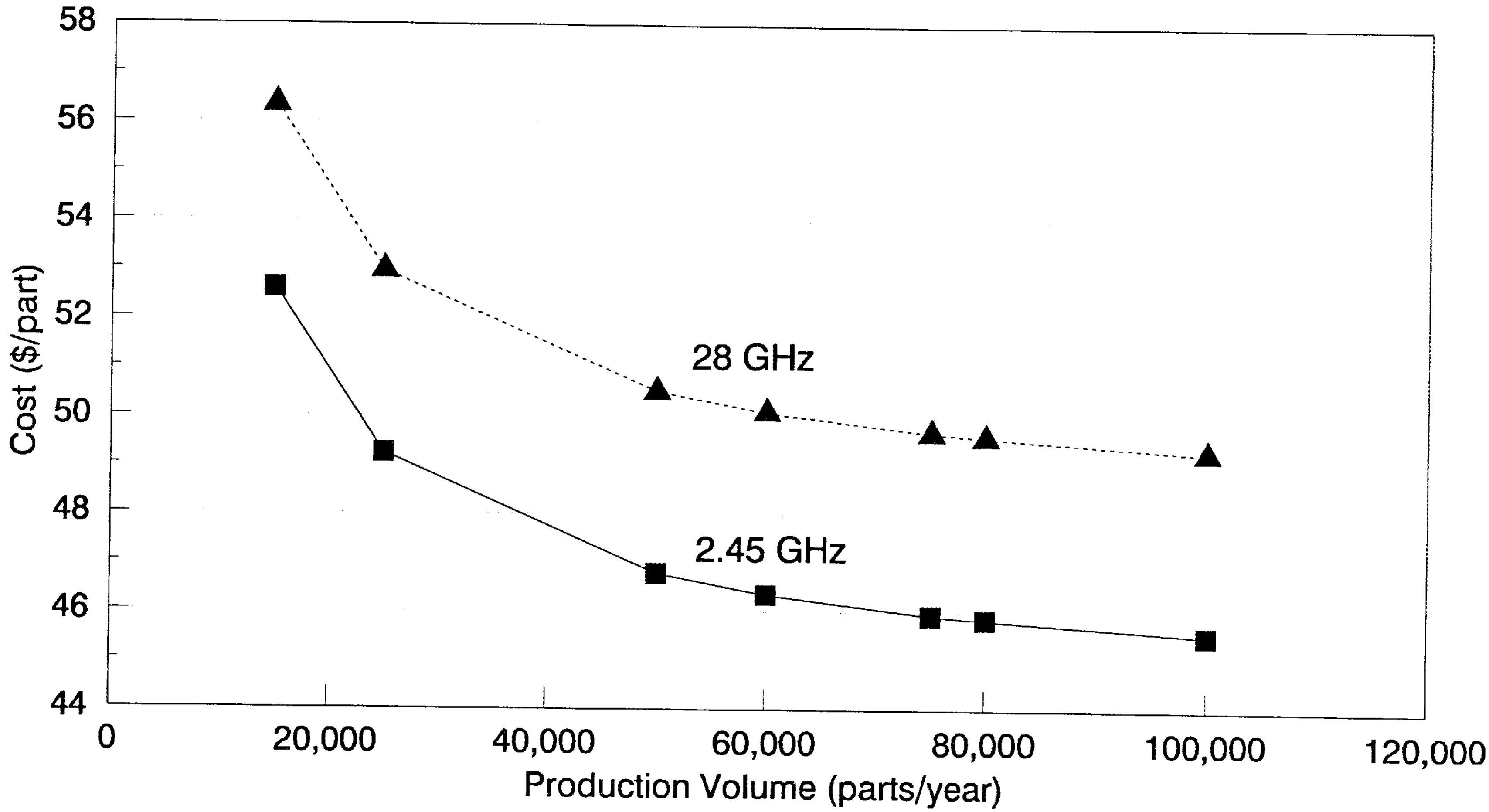

Fig. 4.3. Sensitivity of alumina tile cost to changes in annual production volume.

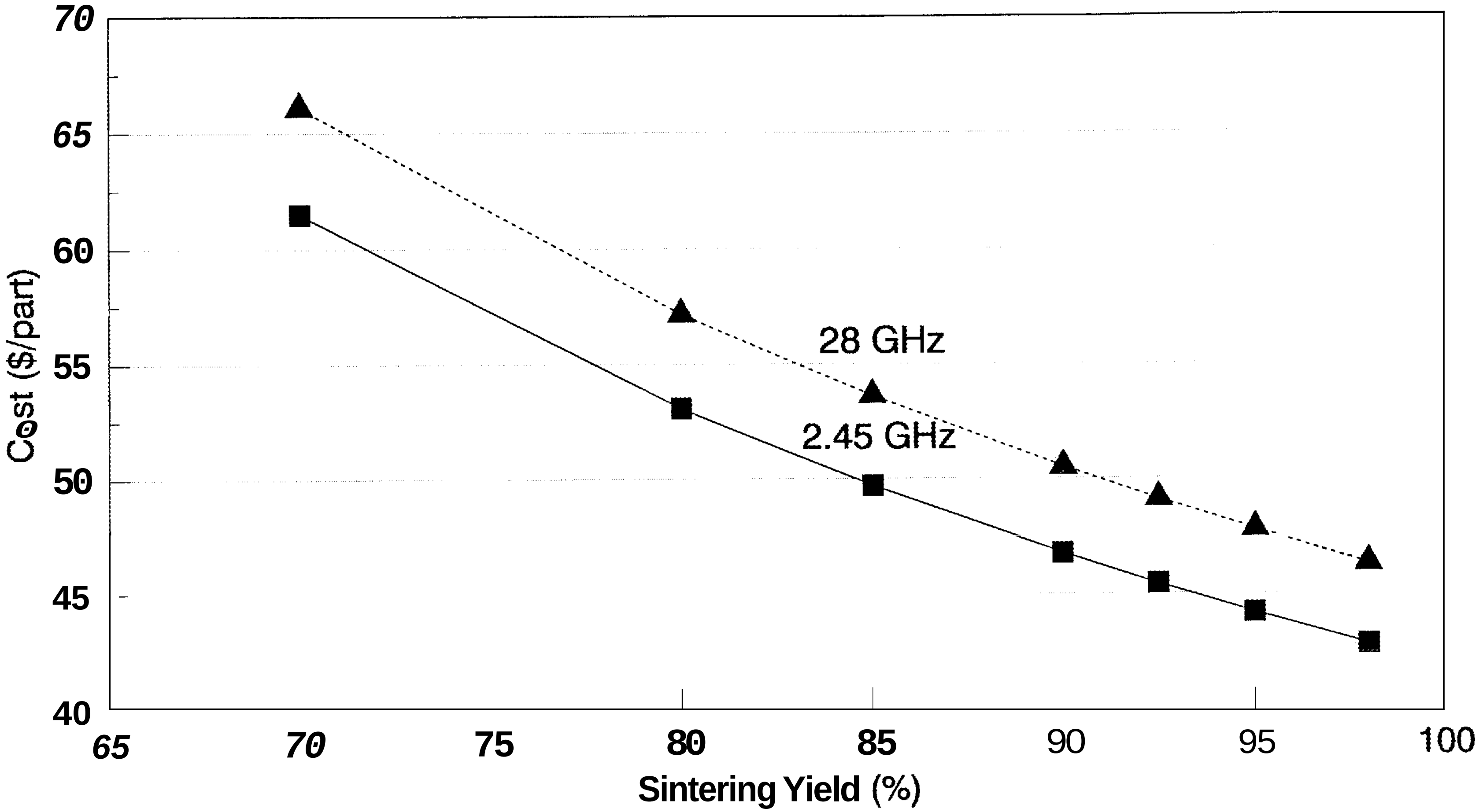

Fig. 4.4. Sensitivity of alumina tile cost to changes in sintering yield.

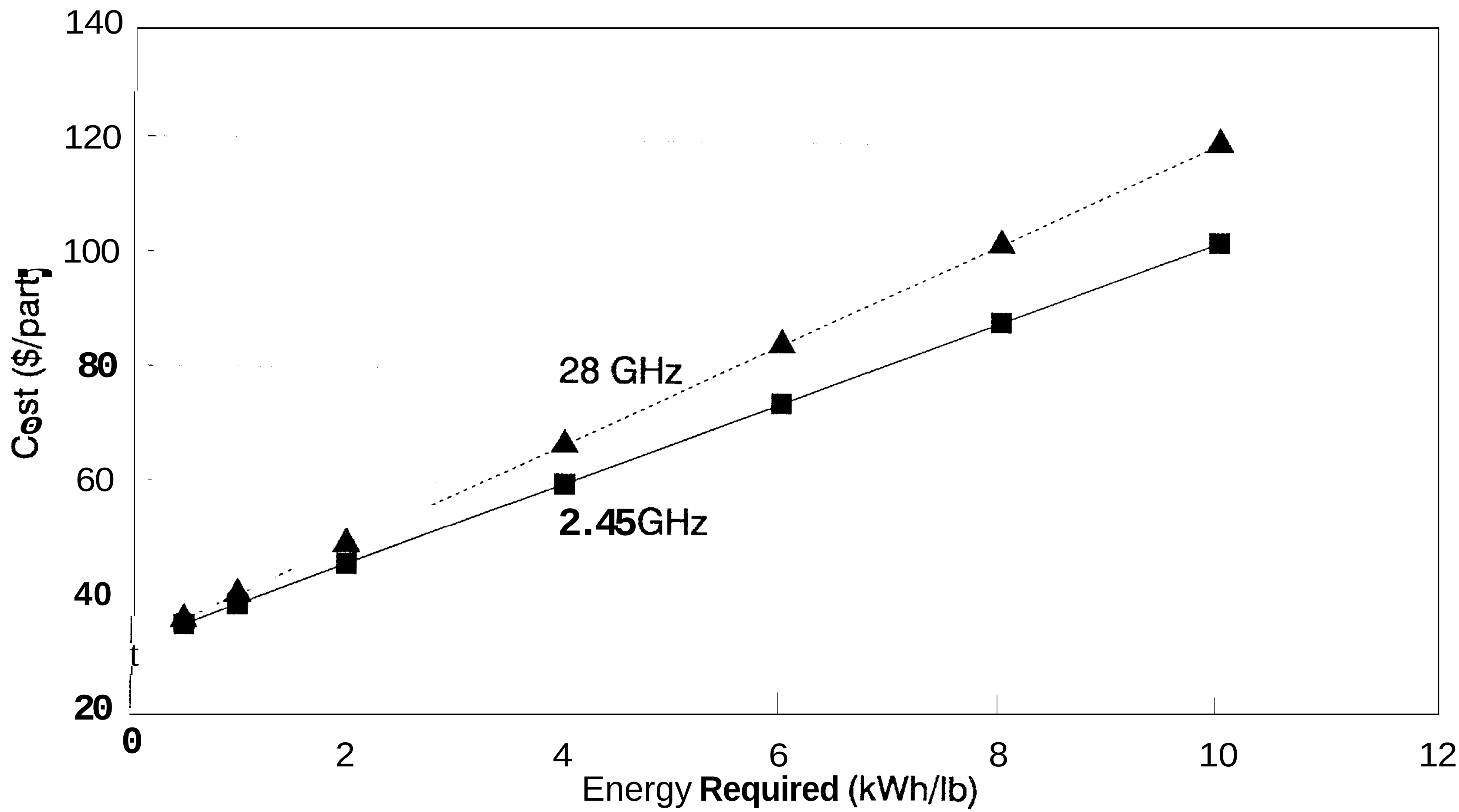

Fig. **4.5.** Sensitivity of alumina tile cost to changes in energy required in sintering.

Table 4.2. Base-Case Assumptions for the Microwave Sintering of Silicon Carbide Tiles

Parameter	**Assumption**
Material	Silicon carbide
Powder Cost	$40/lb (including sintering aids and binder)
Part Size	150 x 150 x 30 mm
Part Weight	4.7 lbs
Annual Production Volume	50,000 parts
Process Step Yields*	
Material Preparation	98%
Isopressing	95%
Green Machining	95%
Sintering	90%
Grinding	95%
Inspection	95%
Total	72%
Firing Heat Efficiency	
2.45 GHz	60%
28 GHz	50%
Labor Cost	$16/h
Microwave Energy Reqd.	2.2 kWh/lb
Cost of Capital ($/KW)	
2.45 GHz	3,000
28 GHz	4,000

*Yield is defined as the physical yield of the process (i.e., 1-scrap rate).

The base-case cost of microwave-sintered silicon carbide tiles is estimated to be \$324.50/part and \$327.50/part under the two given microwave power sources of 2.45 GHz and 28 GHz, respectively. Figure 4.6 shows the distribution of the base-case cost estimates by major cost category. The cost of materials, at about 90% of total cost, is estimated to be the single largest cost component. The high powder cost (i.e., \$40/lb) and the use of expensive insulating materials (i.e., a mixture of boron nitride and glassy carbon, at \$66/lb) at the microwave sintering step contribute to this significantly higher materials cost. Labor costs are next highest and are estimated to contribute less than 5% to total costs. The costs of capital charges and other costs contribute about 2 - 3% each to total costs. The estimated base-case costs are significantly higher than the costs of conventionally-sintered tiles -- almost 1.4 times in the case of the 2.45 GHz system.

More than 80% of the total cost of manufacturing microwave-sintered tiles occurs at the material preparation process step, as shown in Fig. 4.7. The cost of materials (mainly the powder) accounts for more than 98% of the cost at this process step. The cost of firing (i.e., the microwave sintering step) is the next largest cost component, about 13% of the total. The insulation cost at this step is very expensive (as indicated earlier), accounting for 66% of the total process step cost. The other process step costs are significantly less, particularly the pressing and inspection steps, which each contribute less than 1% of the total cost.

4.2.2 Sensitivity Analyses

The process-cost model was used to estimate the technology parameters to which total cost is most sensitive (as was done in the case of alumina armor tiles). These sensitivity tests may provide insights into the future competitiveness of microwave-sintered tiles. Sensitivity analysis was performed on several technical parameters, including annual production volume, sintering yield, and powder cost. The sensitivity of energy requirements at the sintering step for the silicon carbide material is identical to alumina. The following paragraphs discuss the sensitivities of the total cost of microwave-sintered silicon carbide armor tiles to changes in these technical parameters.

4.2.2.1 Annual Production Volume

The sensitivity of the cost of silicon carbide armor tiles to yearly production volume is shown in Fig. 4.8. Tile cost is sensitive to production volume, but the sensitivity decreases as the production volume increases beyond 50,000 parts/yr. At a low production volume of 15,000 parts/yr and for the 2.45 GHz system, tile cost is \$329.30/part; the cost decreases by \$4.80/part when the production volume is increased to 35,000 parts/yr. For the 28 GHz system, the cost sensitivity is found to be similar to that found for the 2.45 GHz system. Higher annual production volume alone will not be sufficient to reduce the cost of microwave-sintered tiles to the cost of conventionally-sintered tiles.

4.2.2.2 Sintering Yield

Figure 4.9 shows the sensitivity of tile cost to changes in yield at the microwave sintering step. For the 2.45 GHz system, the tile cost decreases from \$324.50/part to \$300.10/part as the sintering yield is increased from 90% to 98%. Similar findings are reported for the 28 GHz system. The tile cost could be as low as \$307.90/part if the sintering yield for the 28 GHz system improves to 98%. However, even at this high yield, microwave-sintered tiles are estimated to cost about 1.3 times the cost of conventionally-sintered tiles.

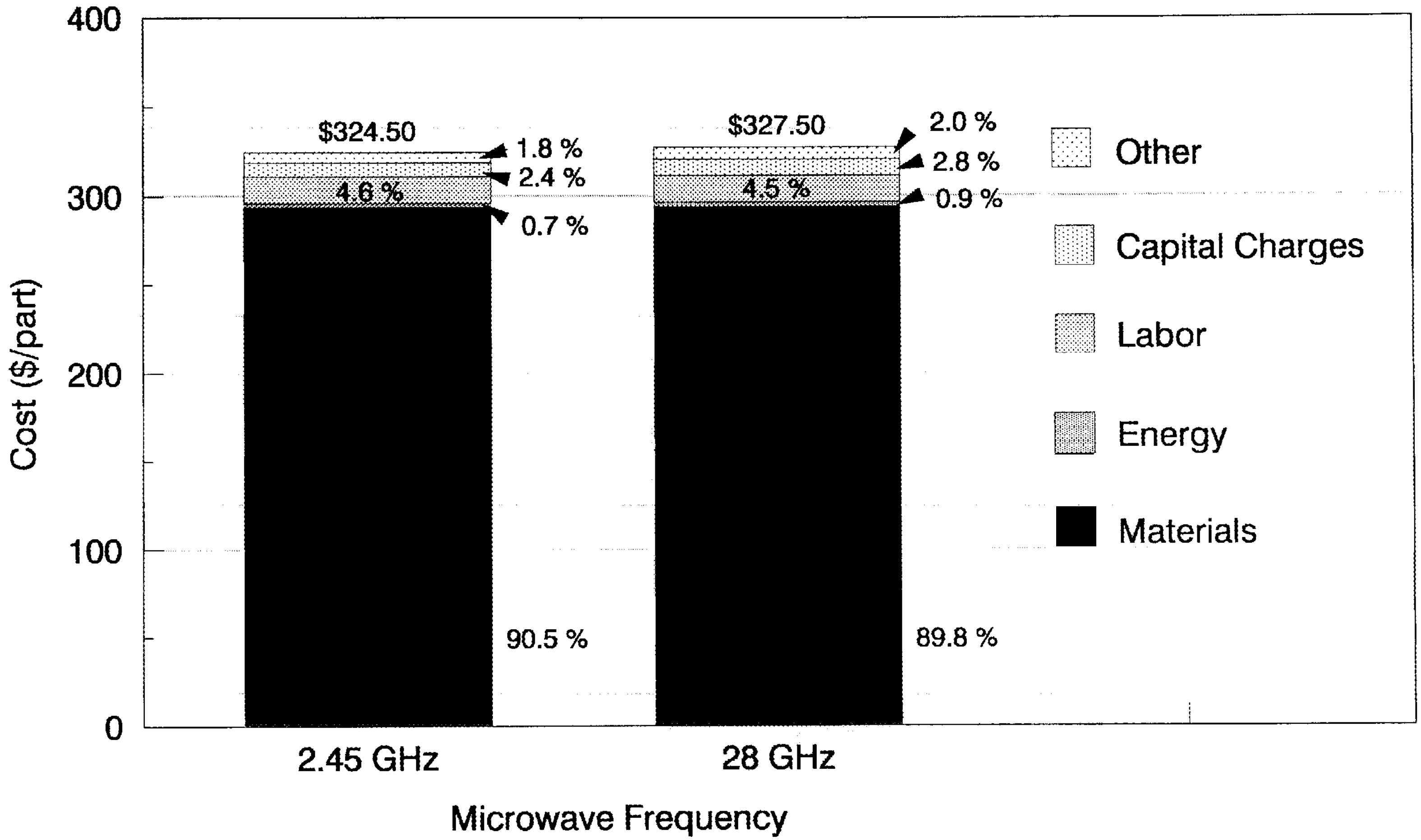

Fig. 4.6. The base-case cost of microwave-sintered silicon carbide tiles.

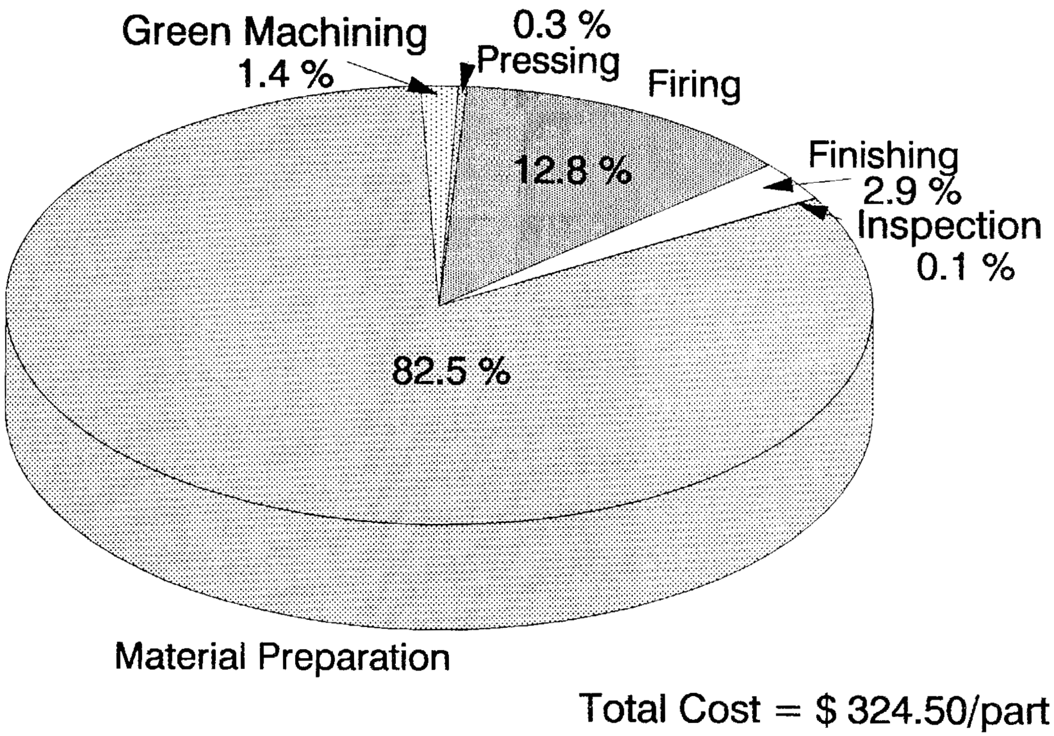

Fig. 4.7. The base-case cost distribution of 2.45 GHz microwave-sintered silicon carbide tiles by process steps.

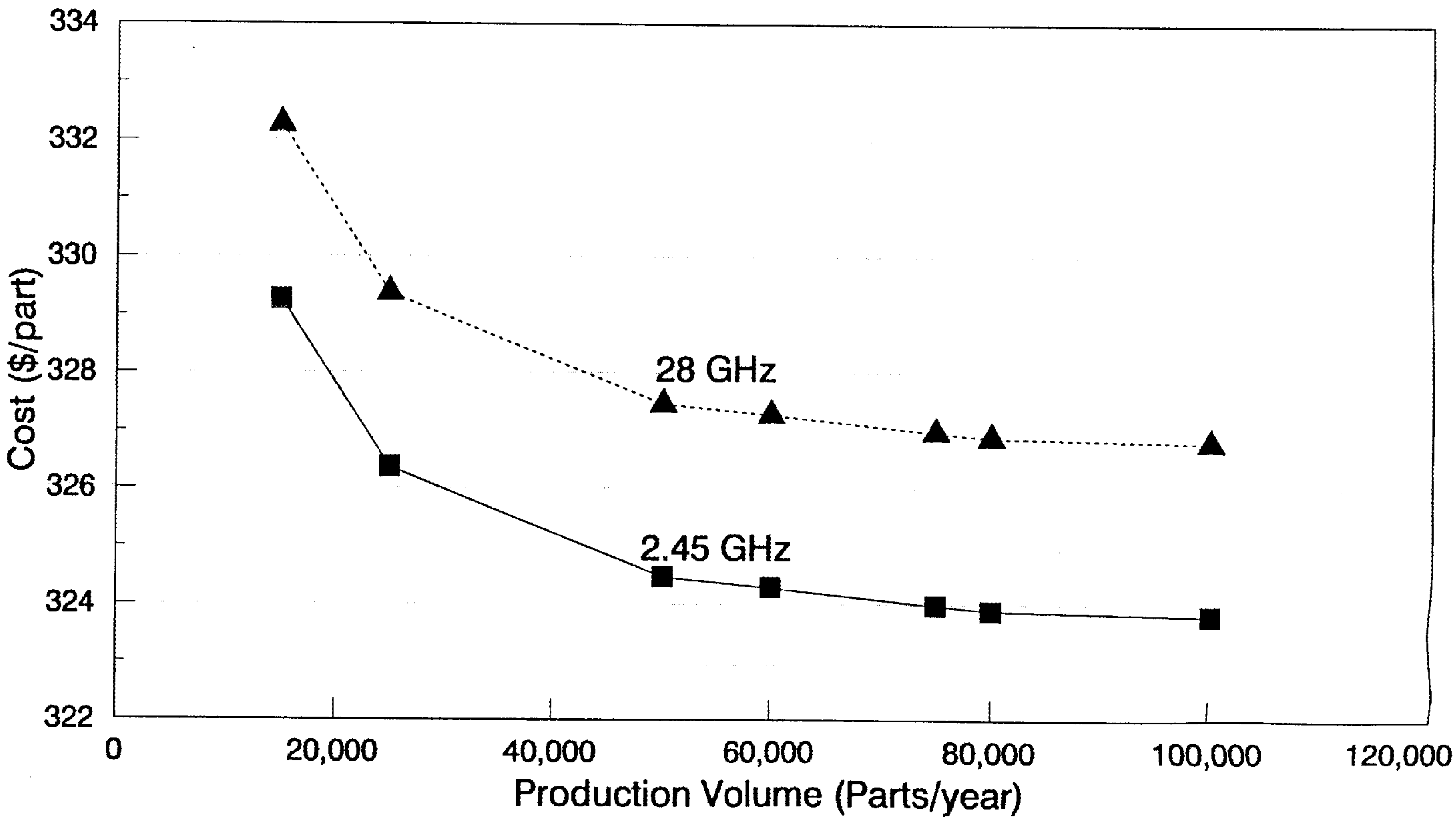

Fig. 4.8. Sensitivity of silicon carbide tile cost to changes in annual production volume.

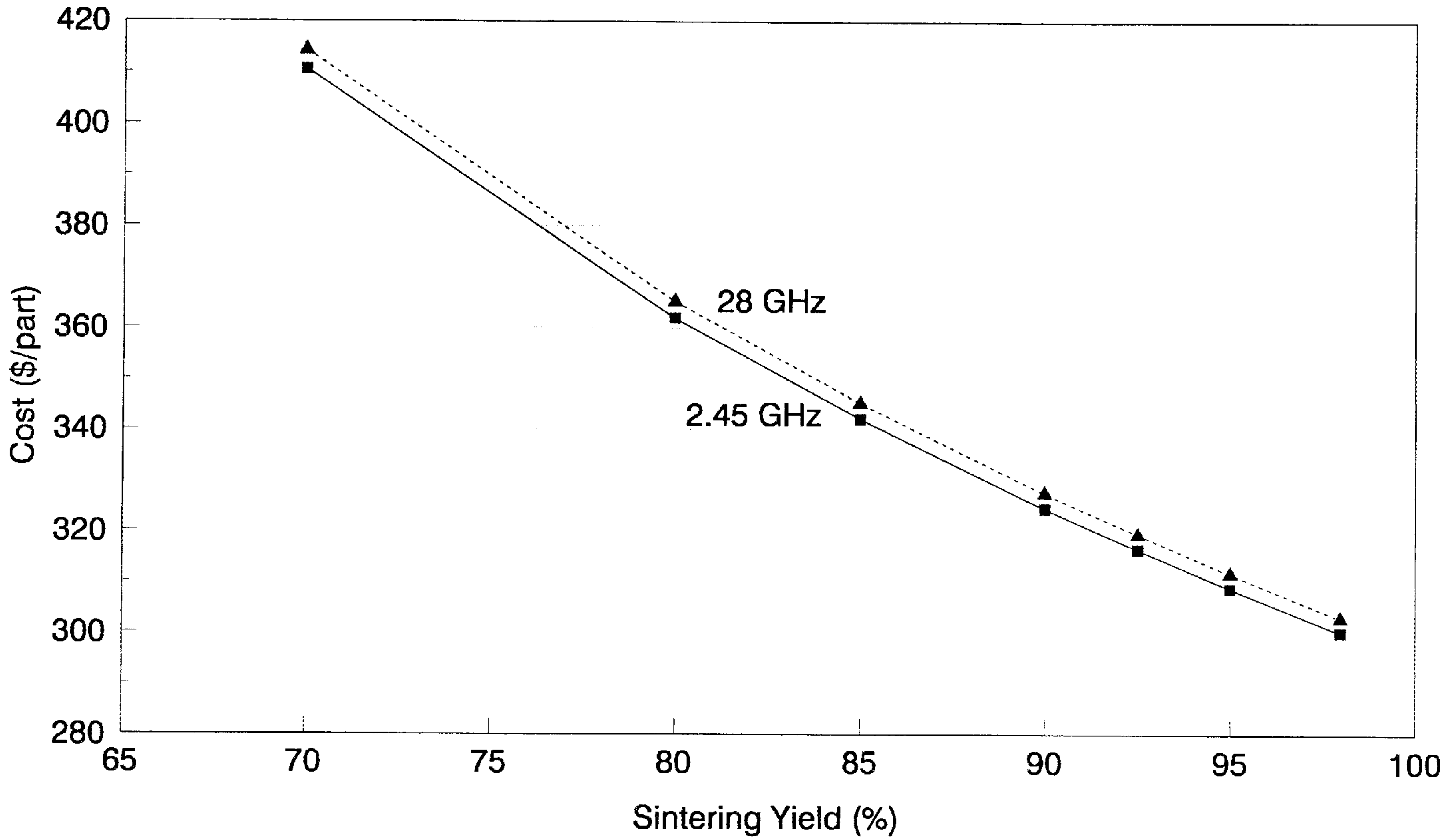

Fig. 4.9. Sensitivity of silicon carbide tile cost to changes in sintering yield.

4.2.2.3 Powder Cost

As discussed earlier, materials contributes about 90% to total cost, with powder cost contributing the major share. A different quality of powder (thereby powder cost) required for microwave-sintered tiles, will substantially change its total cost. Figure 4.10 shows the sensitivity of tile cost to changes in powder cost. Tile cost increases linearly -- $6.6 per unit $/lb increase in the powder cost. If the powder cost is $60/lb (reflecting a high purity quality as compared to a base-case cost of $40/lb), the tile cost is almost double the cost of conventionally-sintered tile. A lower quality of powder (i.e., at a cost of around $25/lb and below) than required for conventionally-sintered tiles, could make the microwave-sintered silicon carbide tiles competitive to similar conventionally-sintered tiles.

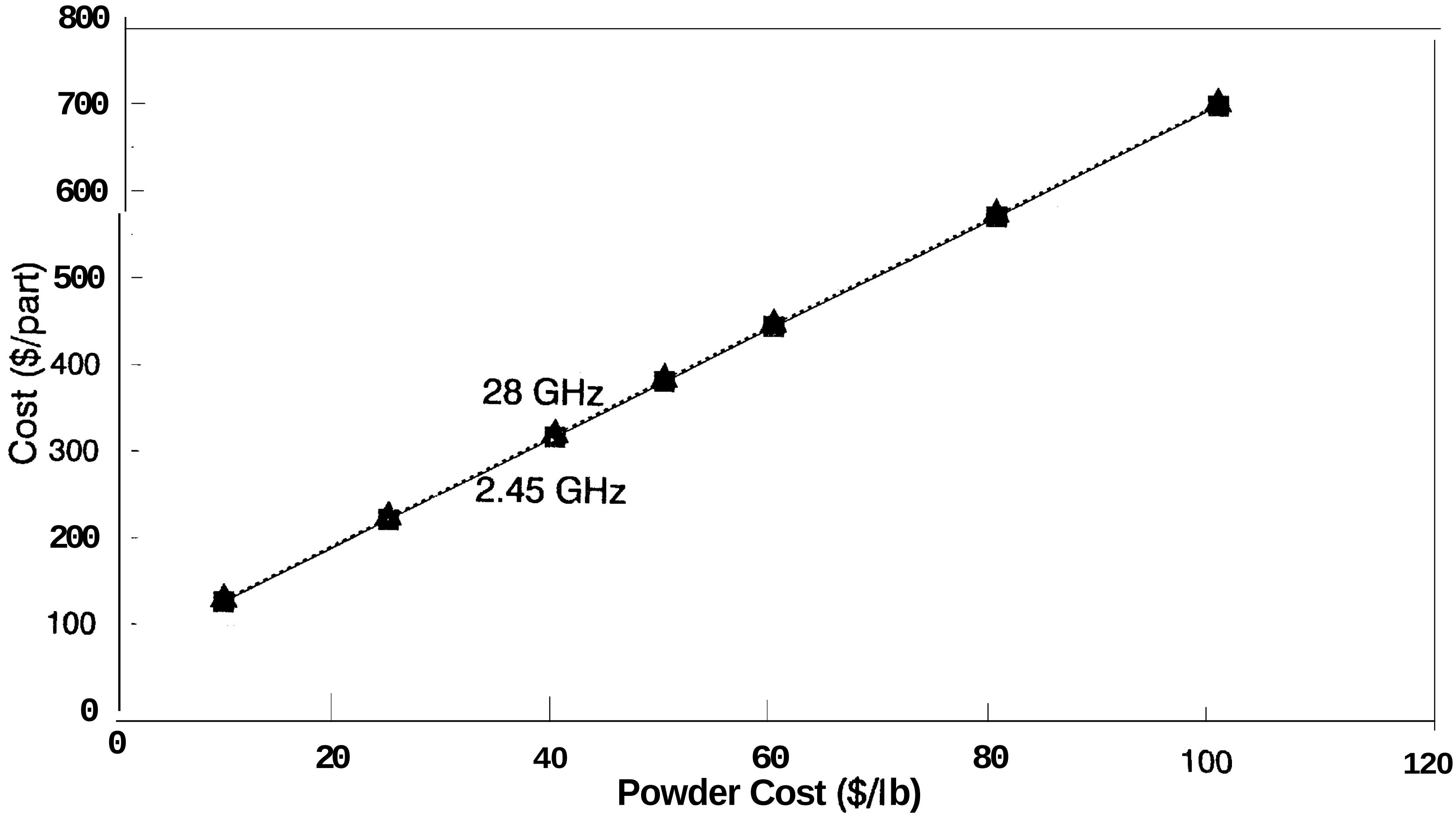

Fig. 4.10. Sensitivity of silicon carbide tile cost to changes in powder cost.

5. CONCLUSIONS

This report extends the preliminary findings of an earlier study (Das and Curlee 1993) which assessed the costs of manufacturing armor tiles using microwave sintering. The model from phase 1 has been extended to include pre- and post-sintering steps. As in the earlier study, this study considers two alternative microwave power sources -- 2.45 GHz and 28 GHz systems -- and two alternative materials, alumina and silicon carbide. Separate models were developed for the two materials, utilizing a process-cost approach within a spreadsheet environment.

Very little detailed technical information is currently available on microwave sintering technology, particularly for the sintering of large ceramic armor tiles. We assume here that the adoption of microwave sintering will not entail numerous changes in the pre- and post-sintering steps and that the values of key technical and economic parameters for those steps will remain identical for both microwave power sources. The manufacturing of microwave-sintered alumina armor tiles will require an additional binder removal step prior to microwave sintering. A single process combined with sintering, as is done in conventional sintering, will cause contamination of parts and furnace surfaces. The base-case cost of microwave-sintered alumina tiles is estimated to be \$46.80/part and \$50.50/part, for 2.45 GHz and 28 GHz microwave power sources, respectively. This is \$5.50/part and \$9.20/part higher than the cost of conventionally-sintered tiles. The higher tile cost for a 28 GHz microwave system results from its lower firing heat efficiency and higher capital cost as compared to a 2.45 GHz microwave system. The additional binder removal step adds only \$0.80/part to the total cost of microwave-sintered tiles.

In the case of microwave-sintered silicon carbide tiles, the material preparation step will be significantly different as compared to conventional sintering. The use of alcohol-based binders will obviate the need for the binder removal step prior to microwave sintering. However, isopressing at the forming step will necessitate an additional green machining step in between the forming and the sintering steps. The base-case costs of microwave-sintered silicon carbide tiles are estimated to be \$324.50/part and \$327.50/part for 2.45 GHz and 28 GHz microwave power sources, respectively, as compared to a value of \$235/part for conventionally-sintered tiles. The significant difference between the cost of silicon carbide and alumina can be attributed primarily to a large difference in powder cost (\$40/lb for silicon carbide vs \$2/lb for alumina).

The cost of materials is estimated to be the largest component of total cost for both ceramic materials (40% for alumina and 90% for silicon carbide). Higher powder cost and expensive insulating materials necessary at the microwave sintering step in the case of silicon carbide contribute to its significanlty higher materials cost. For both materials, energy is the smallest cost component; labor and capital contribute about equal shares to total cost. Material preparation followed by firing are the two most expensive process steps. The material preparation process step contributes 44% of the total cost in the case of alumina tiles and 82.5% of the total cost in the case of silicon carbide tiles. The firing step contributes 38% to total cost in the case of alumina and 12.8% in the case of silicon carbide tiles. Palicka (1992) has similarly shown that the cost of densification (which includes overhead) is the largest cost element in the processing of armor ceramics, ranging between 35% and 60% of the total cost, depending on the ceramic material used.

Several sensitivity analyses of changes in key economic and technical parameters on the costs of microwave-sintered tiles were conducted. Those analyses indicate that costs are quite sensitive to changes in the quantity of microwave energy required during sintering, as was found in the previous study. The cost of silicon carbide tiles is found to be very sensitive to powder cost. If a better quality of powder is necessary in the case of microwave sintering, microwave-sintered silicon carbide tiles are estimated to cost several times higher than the existing conventionally-sintered tiles. Pre- and post-sintering steps are not expected to be significantly more expensive than similar steps for the conventional sintering technology. Thus, the cost at the microwave sintering step will be detrimental to the competitiveness of microwave-sintered tiles.

The cost estimates discussed here are preliminary and should be updated as more technical information becomes available. In particular, we suggest further analysis as more information is available: (1) about the pre- and post-sintering steps and their sensitivities to the frequency of microwave power source used and (2) about energy requirements at the microwave sintering step. The competitiveness of microwave-sintered ceramic tiles will not be determined by the cost of similar conventionally-sintered tiles alone. Rolled, hardened steel armor tiles currently in wide use cost ten times less (on a per-pound basis) than even conventionally-sintered ceramic tiles. Lighter ceramic-armor vehicles may have a lower operation cost due to better fuel efficiency. We suggest, therefore, that cost comparisons be done on a life-cycle/system basis rather than on a first-cost basis. 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 technologies. The present work provides a framework, and a computer model in which new information may easily be assimilated as it becomes available.

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APPENDIX A
A LISTING OF THE ALUMINA ARMOR TILE PROCESS-COST MODEL

	A	B	C	D
1	MICROWAVE SINTERING MODEL			
2	ALUMINA CERAMIC ARMOR TILES			
5	FACTOR PRICES			
6	==	================		
7		units	$/unit	
8		------------------		
9	==========> ENERGY			
10	Electricity	Kwh*	0.08	
11	Natural Gas	MBtu	$6.50	
13		Units	$/unit	
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	Cost of Powder	$/lb	$2.00	
20	Insulation	$/lb	$4.00	
21	Inert Gas Atmosphere	$/cu.ft	$0.30	
24	==========> OTHERS			
25	Direct Labor ($/man-hour)		$16.00	
26	Benefits (% of Direct Labor)		40%	
27	Indirect Labor (% of Direct Labor)		30%	
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	
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	
46	Operating Time	days/yr	250	
47	No. of Shifts/Day		1	
48	No. of Hrs/Shift		8	
49	Production Rate	lb/hr	205	
50	Sintering Yield		90%	

A	A	B	C	D
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	McWAVE 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. (KWh/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%	
78				
79	ASSUMED PROCESS YIELDS			
80	Material Preparation	72%	98%	
81	IsoPressing	73%	95%	
82	Green Machining	77%	95%	
83	Sintering	81%	90%	
84	Grinding	90%	95%	
85	Inspection	95%	95%	
86	Total Yield		72%	
87				
88				
89				
90				

MATERIAL PREPARATION

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Spray Dryer System	1	$153,997	$153,997
Ball Mill	1	$82,132	$82,132
Materials Handling Equipment	1	$23,613	$23,613
Total ($/plant) =>			$259,74[illegible]

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Powder	8.21	$2.00	$16.43	$2.78
Other Binder	N/A	N/A	N/A	N/A
Total =>			$16.43	$2.78

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for blending(kwh)	5.48	0.08	$0.44	$0.07
Natural Gas for Spray Drying (MBtu)	0.06	6.50	$0.40	$0.07
		Total =>	$0.83	$0.14

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours/day)	0.041	$16.00	$0.66	$0.11
Labor Overhead (Indirect + Benefits)		70.0%	$0.46	$0.08
Capital Charges		12.0%	$1.28	$0.22
Taxes + Insurance		2.2%	$0.16	$0.03
Maintenance		10.0%	$0.72	$0.12
Building	1184	0.20	$0.06	$0.01
		Total =>	$3.34	$0.57

==========>COST OF MATERIALS PREPARATION	=>	$20.60	$3.49

COST DISTRIBUTION

Materials	$16.43	80%
Energy	$0.83	4%
Labor	$1.1[illegible]	5%
Capital Charges	$1.28	6%
Other	$0.94	5%

J	K	L	M	N

DRYPRESSING

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Dry Pressing Equipment	2	$250,000	4.64E+05
Total ($/plant) =>			4.64E+05

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Prepared Powder	1.36		$20.60	$3.49
Mold Cost	0.001	$350	$0.19	$0.03
Total =>			$20.79	$3.52

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for pressing(kwh)	0.244	$0.08	$0.020	$0.003
		Total =>	$0.020	$0.003

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.1	$16.00	$1.25	$0.21
Labor Overhead (Indirect + Benefits)		70.0%	$0.87	$0.15
Capital Charges		12.0%	$2.24	$0.38
Taxes + Insurance		2.2%	$0.28	$0.05
Maintenance		10.0%	$1.27	$0.21
Building	928	0.20	$0.06	$0.01
		Total =>	$5.97	$1.01

==========>COST OF DRYPRESSING		=>	$6.18	$1.05
==========>COST AFTER DRYPRESSING		=>	$26.77	$4.54

COST DISTRIBUTION

Materials	$16.62	62.1%
Energy	$0.85	3.2%
Labor	$3.24	12.1%
Capital Charges	$3.52	13.1%
Other	$2.54	9.5%

A	O	P	Q	R	S

BINDER REMOVAL

==========> EQUIPMENT

	UNITS	$/UNIT	$/plant
Binder Removal System	1	$40,000	$36,905
Materials Handling Equipment	0.1	$40,000	$3,690
Total ($/plant) =>			$40,595

==========> PROCESS MATERIALS

	UNITS	$/UNIT	$/piece	$/lb
Pressed Part	1.3		$26.77	$4.54
Total =>			$26.77	$4.54

==========> ENERGY

	UNITS	$/UNIT	$/piece	$/lb
To Heat Insulation (Btu)	870	$0.00001	$0.0057	$0.00
To Evaporate Water (Btu)	1904	$0.00001	$0.0124	$0.00
To Heat Part (Btu)	1467	$0.00001	$0.0095	$0.00
To Heat Incoming Air (Btu)	18	$0.00001	$0.0001	$0.00
To Heat Water In Incoming Air (Btu)	939	$0.00001	$0.0061	$0.00
Soaking Heat (Btu)	939	$0.00001	$0.0061	$0.00
Total Using Assumed Drying Efficiency		=>	$0.0665	$0.000

==========> OTHERS

			$/piece	$/lb
Direct Labor (man-hours/day)	4.0	$16.00	$0.23	$0.04
Labor Overhead (Indirect + Benefits)		70.0%	$0.16	$0.03
Capital Charges		12.0%	$0.19	$0.03
Taxes + Insurance		2.2%	$0.02	$0.00
Maintenance		10.0%	$0.11	$0.02
Building	144	0.20	$0.01	$0.00
		Total =>	$0.71	$0.12

		$/piece	$/lb
==========>COST OF BINDER REMOVAL	=>	$0.78	$0.13
==========>COST AFTER BINDER REMOVAL	=>	$27.55	$4.67

COST DISTRIBUTION

Materials	$16.62	60%
Energy	$0.92	3%
Labor	$3.63	13%
Capital Charges	$3.7[illegible]	13%
Other	$2.[illegible]8	10%

MICROWAVE SINTERING

========> EQUIPMENT	UNITS	$/UNIT	$/plant
McWave System (KW)	357	$3,000	1.07E+06
Materials Handling Equipment	35.7	$3,000	1.07E+05
	Total ($/plant) =>		1.18E+06

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Dried Part	1.23		$27.55	5
Tube	14	$0.02	$0.29	$0.05
Insulation	0.12	$4.00	$0.50	$0.08
Energy	23.8	$0.08	$1.90	$0.32
Inert Gas Atmosphere	0.7	$0.30	$0.20	$0.03
	Total =>		$30.44	$5.16

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours/day)	36.6	$16.00	$3.60	$0.61
Labor Overhead (Indirect + Benefits)		70%	$2.52	$0.43
Capital Charges		12.0%	$5.13	$0.87
Taxes + Insurance		2.2%	$0.64	$0.11
Maintenance		10.0%	$2.90	$0.49
Building	1628	$0.20	$0.10	$0.02
		Total =>	$14.89	$2.52
========>COST OF MCWAVE SINTERING STEP		=>	$17.77	$3.01
========>COST AFTER MICROWAVE SINTERING		=>	$45.33	$7.68

COST DISTRIBUTION

Materials	$17.60	38.8%
Energy	$2.82	6.2%
Labor	$9.75	21.5%
Capital Charges	$8.84	19.5%
Other	$6.32	13.9%

A	Y	Z	AA	AB	AC

MACHINE SHOP

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Grinding Machines	0.4	$25,000	$10,[illegible]
Miscellaneous Tools	0.42	$2,500	$1,044
Total ($/plant) =>			$11,484

====> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Fired Part	1.11		$45.33	$7.68
Coolant	0.01	$0.01	$0.00	$0.00
Grinding Wheels	0.002	$400.0	$0.89	$0.15
Total =>			$46.21	$7.83

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (KWh)	0.132	$0.08	$0.011	$0.002
Total =>			$0.011	$0.002

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours/day)	2.23	$16.00	$0.19	$0.03
Labor Overhead (Indirect + Benefits)		70.0%	$0.13	$0.02
Capital Charges		12.0%	$0.05	$0.01
Taxes + Insurance		2.2%	$0.01	$0.00
Maintenance		10.0%	$0.03	$0.00
Building	73	0.20	$0.00	$0.00
Total =>			$0.40	$0.07

		$/piece	$/lb
==========>COST OF MACHINING	=>	$1.30	$0.22
==========>COST AFTER MACHINING	=>	$46.62	$7.90

COST DISTRIBUTION

Materials	$18.48	40%
Energy	$2.83	6%
Labor	$10.07	22%
Capital Charges	$8.89	19%
Other	$6.35	14%

QUALITY CONTROL AND STORAGE

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Special Tables, Jigs, and Other Miscellaneous Equipment Storage Racks	2.0	$5,000	$10,000
Total ($/plant) =>			$10,000

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Machined Parts	1.05		$46.62	$7.90
Total =>			$46.62	$7.90

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	0.000	0.08	0.00	0.00
Total =>			0.00	0.00

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.333	$16.00	$0.03	$0.00
Labor Overhead (Indirect + Benefits)		70.0%	$0.02	$0.00
Capital Charges		12.0%	$0.04	$0.01
Taxes + Insurance		2.2%	$0.00	$0.00
Maintenance		10.0%	$0.02	$0.00
Building		0.20	$0.04	$0.01
Total =>			$0.15	$0.03

		$/piece	$/lb
==========>COST OF QUALITY CONTROL	=>	$0.15	$0.03
==========>COST AFTER QUALITY CONTROL	=>	$46.78	$7.93

COST DISTRIBUTION

Materials	$18.48	40%
Energy	$2.83	6%
Labor	$10.12	22%
Capital Charges	$8.92	19%
Other	$6.42	14%

TOTALS Microwave Sintering Alumina Ceramic Armor Tile

==========> PROCESS

	$/piece	$/lb	percent
Material Preparation	$20.60	$3.49	44.03%
Pressing	$6.18	$1.05	13.20%
Binder Removal	$0.78	$0.13	1.67%
Firing	$17.77	$3.01	38.00%
Finishing	$1.30	$0.22	2.77%
Inspection	$0.15	$0.03	0.33%
Total =>	$46.78	$7.93	100.00%

==========> PROCESS COSTS

	$/piece	$/lb	Percent
Materials	$18.48	$3.13	39.5%
Energy	$2.83	$0.48	6.1%
Labor	$10.12	$1.71	21.6%
Capital Charges	$8.92	$1.51	19.1%
Other	$6.42	$1.09	13.7%
Total ========>	$46.78	$7.93	

$/kg ====> $17.44

ASSUMPTIONS

Material Selected	Alumina
Powder Cost ($/lb)	$2.00
Firing Method	2.45 Ghz
Total Yield	72%
Production Volume (pc/yr)	50000

APPENDIX B
A LISTING OF THE SILICON CARBIDE ARMOR TILE PROCESS-COST MODEL

MICROWAVE SINTERING MODEL
SILICON CARBIDE CERAMIC ARMOR TILES

FACTOR PRICES

A	B	C	D
	units	$/unit	
==========> ENERGY			
Electricity	Kwh*	0.08	
Natural Gas	MBtu	$6.50	
	Units	$/unit	
==========> MATERIALS			
CHOOSE MATERIAL BY NUMBER ====>	2	3.17	
1. Alumina Standard Powder	gm/cu.cm	3.97	
2. Silicon Carbide Powder	gm/cu.cm	3.17	
Cost of Powder	$/lb	$40.00	
Insulation	$/lb	$66.00	
Inert Gas Atmosphere	$/cu.ft	$0.30	
==========> OTHERS			
Direct Labor ($/man-hour)		$16.00	
Benefits (% of Direct Labor)		40%	
Indirect Labor (% of Direct Labor)		30%	
Cost of Capital (% of initial investment)		12.0%	
Tax Burden + Insurance (% of physical plant)		2.2%	
Maintenance (% of physical plant)		10.0%	
Years to Recover Investment		10	
Building Cost	$/sqft/mo	$0.20	

INPUT FACTORS

Plant Capacity (pieces/yr)		50000	
Part Length	cm	15	
Part Width	cm	15	
Part Thickness	cm	3	
Part Volume	cu. cm	675	
Part Weight	lbs	4.7	
Operating Time	days/yr	250	
No. of Shifts/Day		1	
No. of Hrs/Shift		8	
Production Rate	lb/hr	164	
Sintering Yield		90%	

A	A	B	C	D
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	McWAVE 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. (KWh/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%	
78				
79	ASSUMED PROCESS YIELDS			
80	Material Preparation	72%	98%	
81	DryPressing	73%	95%	
82	Binder Removal	77%	95%	
83	Sintering	81%	90%	
84	Grinding	90%	95%	
85	Inspection	95%	95%	
86	Total Yield		72%	
87				
88	DRYING PARAMETERS			
89	Batch Weight	lbs	197	
90	Specific Weight		0.25	
91	Binder Weight (%)		2%	
92	Thickness of Insulation	ft	0.75	
93	Density of Insulation	lb/cu.ft	12	
94	Furnace Setting Density	lb/cu.ft	50	
95	Furnace Interior Volume	cu.ft	4	
96	Furnace Interior Surface Area	sq.ft	31	
97	Drying Time	hrs	4	
98	Drying Heat Efficiency		60%	
99	Lb Water/Lb Air Entrance		0.04	
100	Lb Water/Lb Air Exit		0.01	

MATERIAL PREPARATION

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Ball Mill	0.5	$65,664	$35,931
Jar Mill Mixer	8	$2,100	$17,237
Screening Equipment	0.2	$12,000	$1,970
Materials Handling Equipment	1	$5,514	$5,514
Total ($/plant) =>			$43,415

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Powder	6.57	$40.00	$262.66	$55.68
Total =>			$262.66	$55.68

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for material preparation	4.88	0.08	$0.39	$0.08
		Total =>	$0.39	$0.08

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours/day)	23.311	$16.00	$2.60	$0.55
Labor Overhead (Indirect + Benefits)		70.0%	$1.82	$0.39
Capital Charges		12.0%	$0.21	$0.05
Taxes + Insurance		2.2%	$0.03	$0.01
Maintenance		10.0%	$0.12	$0.03
Building	1174	0.20	$0.06	$0.01
		Total =>	$4.83	$1.02

==========>COST OF MATERIALS PREPARATION => $267.88 $56.79

COST DISTRIBUTION

Materials	$262.66	98.1%
Energy	$0.39	0.1%
Labor	$4.41	1.6%
Capital Charges	$0.21	0.1%
Other	$0.20	0.1%

ISOPRESSING

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Isopressing Equipment	1.0	$100,000	1.00E+05
Materials Handling Equipment	1.0	$10,000	1.00E+04
			=========
Total ($/plant) =>			1.00E+05

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Prepared Powder	1.36		$267.88	$56.79
Mold Cost	0.001	$20	$0.03	$0.01
			========	========
Total =>			$267.90	$56.79

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for pressing(kwh)	0.235	$0.08	$0.019	$0.004
			========	========
		Total =>	$0.019	$0.004

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours/piece)	0.005	$16.00	$0.07	$0.02
Labor Overhead (Indirect + Benefits)		70.0%	$0.05	$0.01
Capital Charges		12.0%	$0.48	$0.10
Taxes + Insurance		2.2%	$0.06	$0.01
Maintenance		10.0%	$0.27	$0.06
Building	50	0.20	$0.00	$0.00
			========	========
		Total =>	$0.94	$0.20

==========>COST OF ISOPRESSING	=>	$0.99	$0.21
==========>COST AFTER ISOPRESSING	=>	$268.87	$57.00

COST DISTRIBUTION

Materials	$262.68	97.7%
Energy	$0.41	0.2%
Labor	$4.54	1.7%
Capital Charges	$0.70	0.3%
Other	$0.54	0.2%

GREEN MACHINING

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Bandsaw and Accessory Machines	1	$20,000	$20,000
Materials Handling Equipment	0.1	$20,000	$2,000
	Total ($/plant) =>		$22,000

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Pressed Part	1.3		$268.87	$57.00
Tool Inserts	0.006	$400	$2.59	$0.55
	Total =>		$271.46	$57.55

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for Machining (kWh)	0.10	$0.08	$0.01	$0.00
	Total =>		$0.01	$0.00

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours/piece)	0.06	$16.00	$1.04	$0.22
Labor Overhead (Indirect + Benefits)		70.0%	$0.73	$0.15
Capital Charges		12.0%	$0.10	$0.02
Taxes + Insurance		2.2%	$0.01	$0.00
Maintenance		10.0%	$0.06	$0.01
Building	20	0.20	$0.00	$0.00
		Total =>	$1.93	$0.41

==========>COST OF GREEN MACHINING		=>	$4.53	$0.96
==========>COST AFTER GREEN MACHINING		=>	$273.40	$57.96

COST DISTRIBUTION

Materials	$265.27	97.0%
Energy	$0.42	0.2%
Labor	$6.30	2.3%
Capital Charges	$0.80	0.3%
Other	$0.61	0.2%

MICROWAVE SINTERING

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
McWave System (KW)	285	$3,000	8.55E+05
Materials Handling Equipment	28.5	$3,000	8.55E+04
			=========
Total ($/plant) =>			9.41E+05

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Dried Part	1.23		$273.40	58
Tube	11	$0.02	$0.23	$0.05
Insulation	0.41	$66.00	$27.28	$5.78
Energy	19.0	$0.08	$1.52	$0.32
Inert Gas Atmosphere	0.7	$0.30	$0.20	$0.04
			=========	=========
Total =>			$302.63	$64.15

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours/day)	30.8	$16.00	$3.03	$0.64
Labor Overhead (Indirect + Benefits)		70%	$2.12	$0.45
Capital Charges		12.0%	$4.10	$0.87
Taxes + Insurance		2.2%	$0.51	$0.11
Maintenance		10.0%	$2.32	$0.49
Building	1340	$0.20	$0.08	$0.02
			=========	=========
		Total =>	$12.16	$2.58

========>COST OF MCWAVE SINTERING STEP	=>	$41.39	$8.77
========>COST AFTER MICROWAVE SINTERING	=>	$314.79	$66.73

COST DISTRIBUTION

Materials	$292.98	93.1%
Energy	$1.94	0.6%
Labor	$11.46	3.6%
Capital Charges	$4.90	1.6%
Other	$3.52	1.1%

MACHINE SHOP

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Rotary Grinding Machines	5.8	$120,000	$695,996
Miscellaneous Tools	5.8	$12,000	$69,600
Total ($/plant) =>			$765,596

====> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Fired Part	1.11		$314.79	$66.73
Coolant	0.01	$0.01	$0.00	$0.00
Grinding Wheels	0.001	$800	$0.89	$0.19
Total =>			$315.68	$66.92

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (KWh)	2.755	$0.08	$0.220	$0.047
Total =>			$0.220	$0.047

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours/day)	23.20	$16.00	$1.95	$0.41
Labor Overhead (Indirect + Benefits)		70.0%	$1.37	$0.29
Capital Charges		12.0%	$3.00	$0.64
Taxes + Insurance		2.2%	$0.37	$0.08
Maintenance		10.0%	$1.70	$0.36
Building	580	0.20	$0.03	$0.01
Total =>			$8.42	$1.79

			$/piece	$/lb
==========>COST OF MACHINING		=>	$9.53	$2.02
==========>COST AFTER MACHINING		=>	$324.32	$68.75

COST DISTRIBUTION

Materials	$293.87	91%
Energy	$2.16	1%
Labor	$14.78	5%
Capital Charges	$7.90	2%
Other	$5.62	2%

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QUALITY CONTROL AND STORAGE

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Special Tables, Jigs, and Other Miscellaneous Equipment	2.0	$5,000	$10,000
Storage Racks			
Total ($/plant) =>			$10,000

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Machined Parts	1.05		$324.32	$68.75
Total =>			$324.32	$68.75

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	0.000	0.08	0.00	0.00
Total =>			0.00	0.00

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.333	$16.00	$0.03	$0.01
Labor Overhead (Indirect + Benefits)		70.0%	$0.02	$0.00
Capital Charges		12.0%	$0.04	$0.01
Taxes + Insurance		2.2%	$0.00	$0.00
Maintenance		10.0%	$0.02	$0.00
Building		0.20	$0.04	$0.01
Total =>			$0.15	$0.03

		$/piece	$/lb
==========>COST OF QUALITY CONTROL	=>	$0.15	$0.03
==========>COST AFTER QUALITY CONTROL	=>	$324.47	$68.78

COST DISTRIBUTION

Materials	$293.87	91%
Energy	$2.16	1%
Labor	$14.83	5%
Capital Charges	$7.94	2%
Other	$5.68	2%

A	AI	AJ	AK	AL	AM

TOTALS Microwave Sintering Silicon Carbide Ceramic Armor Tile

==========> PROCESS

	$/piece	$/lb	percent
Material Preparation	$267.88	$56.79	82.56%
Pressing	$0.99	$0.21	0.30%
Green Machining	$4.53	$0.96	1.40%
Firing	$41.39	$8.77	12.76%
Finishing	$9.53	$2.02	2.94%
Inspection	$0.15	$0.03	0.05%
Total =>	$324.47	$68.78	100.00%

==========> PROCESS COSTS

	$/piece	$/lb	Percent
Materials	$293.87	$62.30	90.6%
Energy	$2.16	$0.46	0.7%
Labor	$14.83	$3.14	4.6%
Capital Charges	$7.94	$1.68	2.4%
Other	$5.68	$1.20	1.8%
Total ========>	$324.47	$68.78	

$/kg ====> $151.33

ASSUMPTIONS

Material Selected	Silicon Carbide
Powder Cost ($/lb)	$40.00
Firing Method	2.45 Ghz
Total Yield	72%
Production Volume (pc/yr)	50000

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