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The Cost of Silicon Nitride Powder: What Must It Be To Compete?

Sujit Das
T. Randall Curlee

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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THE COST OF SILICON NITRIDE POWDER: WHAT MUST IT BE TO COMPETE?

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ABSTRACT

The ability of advanced ceramic components to compete with similar metallic parts will depend in part on current and future efforts to reduce the cost of ceramic parts. This paper examines the potential reductions in part cost that could result from the development of less expensive advanced ceramic powders. The analysis focuses specifically on two silicon nitride engine components -- roller followers and turbocharger rotors.

The results of the process-cost models developed for this work suggest that reductions in the cost of advanced silicon nitride powder from its current level of about $20 per pound to about $5 per pound will not in itself be sufficient to lower the cost of ceramic parts below the current cost of similar metallic components. This work also examines if combinations of lower-cost powders and further improvements in other key technical parameters to which costs are most sensitive could push the cost of ceramics below the cost of metallics. Although these sensitivity analyses are reflective of technical improvements that are very optimistic, the resulting part costs are estimated to remain higher than similar metallic parts.

Our findings call into question the widely-held notion that the cost of ceramic components must not exceed the cost of similar metallic parts if ceramics are to be competitive. Economic viability will ultimately be decided not on the basis of which part is less costly, but on an assessment of the marginal costs and benefits provided by ceramics and metallics. This analysis does not consider the benefits side of the equation. Our findings on the cost side of the equation suggest that the competitiveness of advanced ceramics will ultimately be decided by our ability to evaluate and communicate the higher benefits that advanced ceramic parts may offer.

1. INTRODUCTION

In recent years, advanced structural ceramics have made significant inroads into applications that have been served traditionally by metallics, such as biomaterials, wear parts, and cutting tools. Further encroachments into these and other markets dominated by metallics -- such as reciprocating engine components, heat exchangers, and bearings -- are expected. It is generally recognized, however, that the reliability and affordability of ceramics must be improved if ceramics are to become a widespread alternative to metallics. Sheppard (1991) suggests that successful commercialization of advanced ceramics depends on providing reliable components at competitive prices comparable in quality and price to their metallic counterparts.

Integrated cost-effective manufacturing is the major objective of many current R&D programs targeted at reducing the costs of ceramics. Finishing and machining operations to form a part to its final shape and nondestructive testing to ensure reliability constitute a major proportion of production costs. Therefore, the development of processes that can reliably fabricate a component to its final shape is crucial. To improve properties and reliability, various advanced ceramic processing technologies are currently under development, such as high-pressure processing, chemical processing, a combination of both, the direct metal oxidation process, and self-propagating high-temperature synthesis.

Other work is directed at reducing the cost of reproducible uniform quality powders needed to fabricate reliable advanced ceramic components with a minimum number of intermediate steps. Depending on the particular ceramic part, materials are estimated to currently contribute between 40% and 60% of total manufacturing cost (Rothman, 1985). Sheppard (1991) reports that several firms and research institutions (e.g., the Diamonite Products Division of W. R. Grace & Co. and the U.S. Naval Research Laboratory) are currently addressing the possibility of manufacturing silicon nitride powder for low-temperature wear applications in the $5/lb price range. Silicon nitride powders suitable for advanced ceramic applications currently cost about $20/lb.

This paper focuses on the contribution that lower-cost powders could make toward improving the economic viability of advanced silicon nitride components as alternatives to similar metallic parts. For the purposes of this analysis, we accept Sheppard's assertion that ceramic parts must cost no more than similar metallic parts if ceramics are to compete. We therefore examine how much the cost of silicon nitride powder must be reduced in order for silicon nitride components to be "competitive" with similar metallic components. Realizing that reductions in powder cost may not alone be sufficient to insure the economic viability of advanced ceramic parts, an assessment of powder cost is also made in combination with potential improvements in other key technical and economic parameters of the manufacturing technology.

Our assumption that ceramic parts must not exceed the cost of metallic parts may not be valid given that some properties of ceramics parts are superior and others inferior to parts made from metallics. The economic viability of advanced ceramics will depend on the balance of marginal costs and benefits provided by ceramics and metallics. However, this simplifying assumption offers a starting point for the analysis and may, in fact, closely reflect the actual decision process in the early stages of adoption.

Two automotive engine parts are considered in the analysis -- i.e., roller followers and turbocharger rotors. These parts are representative of the spectrum of complexity of advanced ceramic components. Silicon nitride turbochargers are, perhaps, the most exciting and demanding engine application of advanced ceramics. Ceramics offer the benefit of low inertia, which reduces turbocharger lag. About 10,000 turbochargers per month are used in Nissan's 300ZX and other cars, all built and sold only in Japan. A high-pressure technology -- sintering in a reactive gas overpressure of nitrogen pressure (as high as 2,000 atmos. pressure) -- is used to commercially manufacture these turbocharger rotors in Japan. In the United States, with the exception of a very limited production run by Buick, ceramic turbochargers have yet to be used in any passenger car. However, ceramic turbochargers supplied by Schwitzer, Holset, Garrett, and Mitsubishi, are currently being used in diesel engines in small pickup trucks, such as those made by Dodge and Ford (F-250 & F-350). Inconel 713C superalloy is the conventional material used for turbocharger rotors, and these metallic turbocharger rotors currently cost about $15 to $20/piece (Srinivasan, 1991).

Numerous options are currently being considered by the automotive industry to improve the reliability and efficiency of valve-train performance in four-cylinder in-line gasoline engines. Among these options are alternative designs of overhead camshafts with a simple rail-type rocker arms, including the replacement of the hardened steel wear pad on the rocker arm with a silicon nitride roller follower. Steel followers with needle bearings are currently being used in the rocker arms of most Ford engines. Mitsubishi uses sintered silicon nitride ceramic rocker arm pads in its taxicabs that are used in Japan. Other innovative options include coating the camshaft lobes with a wear resistant coating and replacing the valves with lightweight titanium alloy valves. Das and Curlee (1989) provide preliminary cost estimates of some of the options currently being considered by the industry. According to Sherman (1991), existing steel followers with needle bearings cost $0.60/piece, a cost that we assume silicon nitride followers must achieve to be competitive with existing steel followers.

2. APPROACH

Our basic approach is to utilize process-cost models to estimate the contribution that lower-cost silicon nitride powders could make toward reducing the costs of silicon nitride turbocharger rotors and roller followers. A base-case set of assumptions is given which is an optimistic representation of current or near-term economic and technology conditions. The costs of our representative engine parts are estimated given these base-case assumptions. These estimates are followed by an analysis of the sensitivity of base-case costs to reductions in the cost of silicon nitride powder.

Given that improvements are expected along technical frontiers other than powder production, the contribution of lower cost powders in reducing part cost is also assessed when combined with other improvements in production technology. Our process-cost models are first used to determine the technical parameters to which production costs are most sensitive. Those technical parameters are then varied in combination with reductions in powder cost to estimate the overall impacts on part costs.

Process-cost models developed by Poggiali (1985) at the Massachusetts Institute of Technology's (MIT) Materials Systems Laboratory were used as the starting point for the models used here. In process-cost modeling, each production step involved in a particular technology is modeled individually, and the values of all the 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, equipment, and capital, each of which is process dependent. The output for 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. 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 in a cost estimation of ceramic tubes and headers used in advanced heat exchangers.

Isopressing and injection-molding manufacturing methods are considered for roller followers and turbocharger rotors, respectively. The slip-casting method (not considered here) is another route for manufacturing turbocharger rotors. Slip-cast parts are less dense than those produced by injection molding, and with current technology would require hot isostatic pressing to achieve final density. German et al. (1991) discuss key issues, such as powders, mixing, and dimensional integrity in powder injection molding, that need to be solved for the process to become the choice for forming existing and emerging materials into precise, high-quality components.

Extensive enhancements were made to the MIT models with respect to key technical and economic input parameters and functional relationships. Enhancements of functional relationships were similar to the ones discussed in Das, Curlee, and Whitaker (1988). Wittmer (1991) provided values for the key technical and economic input parameters of both models. Srinivasan (1991) provided an assessment of the models used in our analysis.

The MIT cutting-tool inserts model, used as the starting point for our roller-follower model, specifically considers six process steps in the following order: material preparation, isopressing, binder removal, firing (periodic and continuous), machine shop, and quality control and storage. The roller follower considered here is essentially a cylindrical tube approximately 0.5 in. long. Outer and inner diameters are assumed to be 0.7 in. and 0.3 in., respectively. Roller followers are processed by wet milling powders, spray drying, and dry pressing. Drying is not required, and binder removal is accomplished in a co-binder/sinter type furnace. Crowning and grinding are the most critical manufacturing steps, as the contact between the follower and the camshaft must be accurate and precise.

The MIT turbocharger rotor model was used as the starting point for our turbocharger rotor model. The process steps in the turbocharger rotor model are identical to the roller-follower model, with the exception that the isopressing process step in the former model is replaced by the injection-molding process step in the latter model. A single machining step is considered immediately after sintering, when both flash sprue removal and final machining are done. The final rotor weight considered for this analysis is 0.62 lb; the green part weighs approximately 1 lb, assuming a binder weight of 38%. This weight is equivalent to a rotor for the Garrett T-3 type turbocharger assembly used in Buick, Saab, and Volvo, which is fabricated from silicon nitride with a density of 3.2 gm/cc. Continuous sintering is assumed to be done at 1700°C in a flowing nitrogen atmosphere. See Appendix A and B for a complete listing of the inputs used in the roller follower and turbocharger rotor models, respectively.

3. MODEL RESULTS

3.1 Roller Followers

3.1.1 Base-Case Results

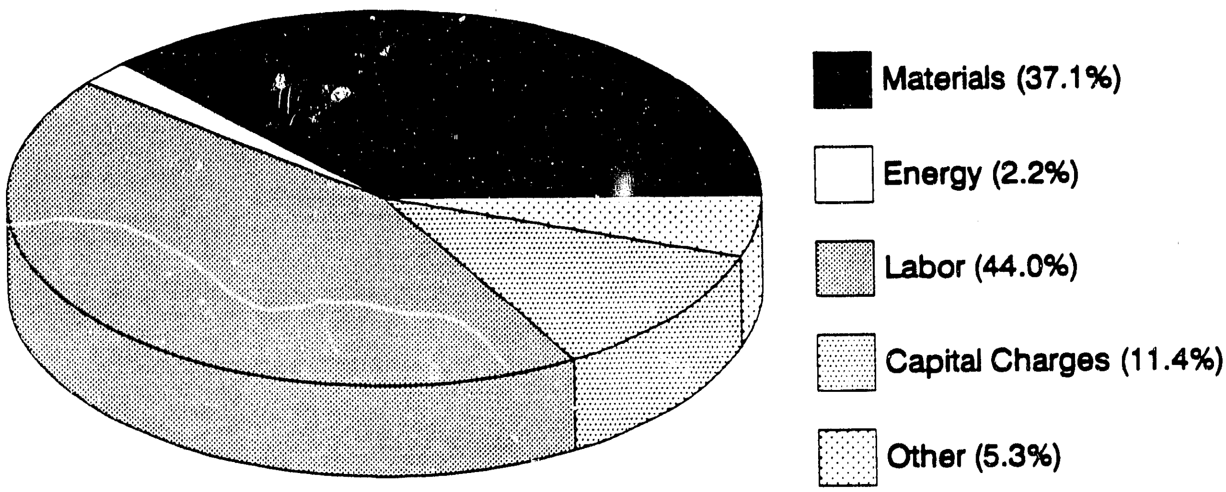
Table 3.1 lists the major base-case assumptions used to estimate the cost of roller followers using the enhanced MIT cutting-tool model. Note that silicon nitride powder is assumed to cost $20/lb in the base case. Other assumptions reflect current or near-term state-of-the-art manufacturing processes.

Table 3.1 Base-case assumptions for roller followers

Part Weight	0.02 lbs
Powder Cost (includes sintering aids)	$20/lb
Max. Production Volume	10,000,000 parts/year
Process Step Yields*	
Materials Preparation	99%
Pressing	99%
Binder Removal	98%
Sintering	95%
Grinding	98%
Inspection	98%
Total Yield	88%
Binder Removal Time	8 hrs
Sintering	1700° C in N_2 atmosphere
Grinding Rate	30 parts/hr
Labor Cost	$13.50/hr
Total Capital Cost (at Max. Production Volume)	$8 M
Cost of Capital	12%

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

Figure 3.1 gives the estimated base-case cost and its distribution by major cost category for manufacturing roller followers using the assumed isopressing technology. The cost of labor, at 44% of total cost, is estimated to be the largest cost component, considerably higher than the cost of materials. Eighty-five percent of total labor cost occurs at the finishing step, for which a tight input tolerance is required. Materials costs are second highest and are estimated to contribute 37.1% to total costs. The costs of capital charges, other inputs, and energy follow in terms of their overall contributions to the cost of manufacturing roller followers.



Total Cost ($ 1.32/piece)

Figure 3.1 Estimated base-case cost of manufacturing silicon nitride roller followers.

Assumptions: Total Yield : 87.6%
Powder Cost : $20/lb (Silicon Nitride Powder = $17.29/lb with Yttrium Oxide as sintering aid)
Grinding Rate : 30 pieces/hr

TUOLFLA.DRW (12-91)

The base case cost of a roller follower is estimated to be $1.32 per piece, as compared to $0.60 for existing steel followers with needle bearings. Therefore, silicon nitride roller followers are not competitive with conventional steel parts under our base-case assumption.

The sensitivity of roller follower cost to reductions in powder costs (including sintering aids Al_2O_3 and Y_2O_3 or La_2O_3) is illustrated in Figure 3.2. Powder composition is assumed to be 85% silicon nitride, 13% yttrium or lanthanum oxide, and 2% alumina. The solid line represents total powder cost, including sintering aids. The dotted line represents the cost of silicon nitride powder only, given that yttrium oxide is used as the sintering aid. The dashed line represents the cost of silicon nitride powder only, given that lanthanum oxide is used as the sintering aid.

For our base-case follower cost of $1.32 per piece, total powder cost is $20/lb. For a total powder cost of $20/lb, the cost of silicon nitride powder is $22.65/lb if La_2O_3 is used as the sintering aid and $17.29/lb if Y_2O_3 is used. For any given follower cost, silicon nitride powder cost is higher with the less expensive sintering aid, La_2O_3 ($5/lb), than with the more expensive Y_2O_3 ($40/lb). The estimated cost of a follower increases linearly by $0.02/piece with a unit increase ($/lb) in total powder cost. The difference in follower cost due to the use of the two different sintering aids is near constant over the cost range examined. A follower is estimated to be $0.10 cheaper when La_2O_3 is used as a sintering aid as compared to Y_2O_3.

Figure 3.2 indicates that if total powder cost is reduced to $10/lb (which reflects a $5.53/lb cost for silicon nitride powder if Y_2O_3 is used as the sintering aid) the cost of a roller follower is estimated to be reduced to $1.11/piece. This cost is almost twice the cost of existing metallic parts. Given that high-quality silicon nitride powders are unlikely to go below $5 to $6 per pound in the foreseeable future, the model suggests that a lower silicon powder cost will not alone be sufficient to make silicon nitride followers competitive with existing metallic counterparts.

3.1.2 Sensitivity Analyses

Given that cost-reducing improvements are likely along several technology fronts, our process-cost model was exercised to estimate the technology parameters to which total cost is most sensitive. Sensitivity analyses were performed on several technical parameters, including total yield, annual production volume, and grinding rate. The following subsections examine how reductions in powder cost, in combination with other technology improvements that lower cost, could affect the total cost of roller followers.

3.1.2.1 Total Yield vs Follower Cost

In our process-cost models, total yield is defined as the product of the individual process yields. A uniform technical change in all individual process steps is considered by means of a "technology factor," a multiplicative factor common to all individual process step yields. Here, variations in total yield are examined by varying the technology factor. A technology factor range of 0.95 to 1.02 corresponds to a total yield range of 64.4% to 98.7%.

Figure 3.3 illustrates the estimated relationship between follower cost and total yield. Follower cost varies linearly $0.01/piece with a 1% change in total yield. Cost of a follower can be as low as $1.22 when total yield is 98.7%.

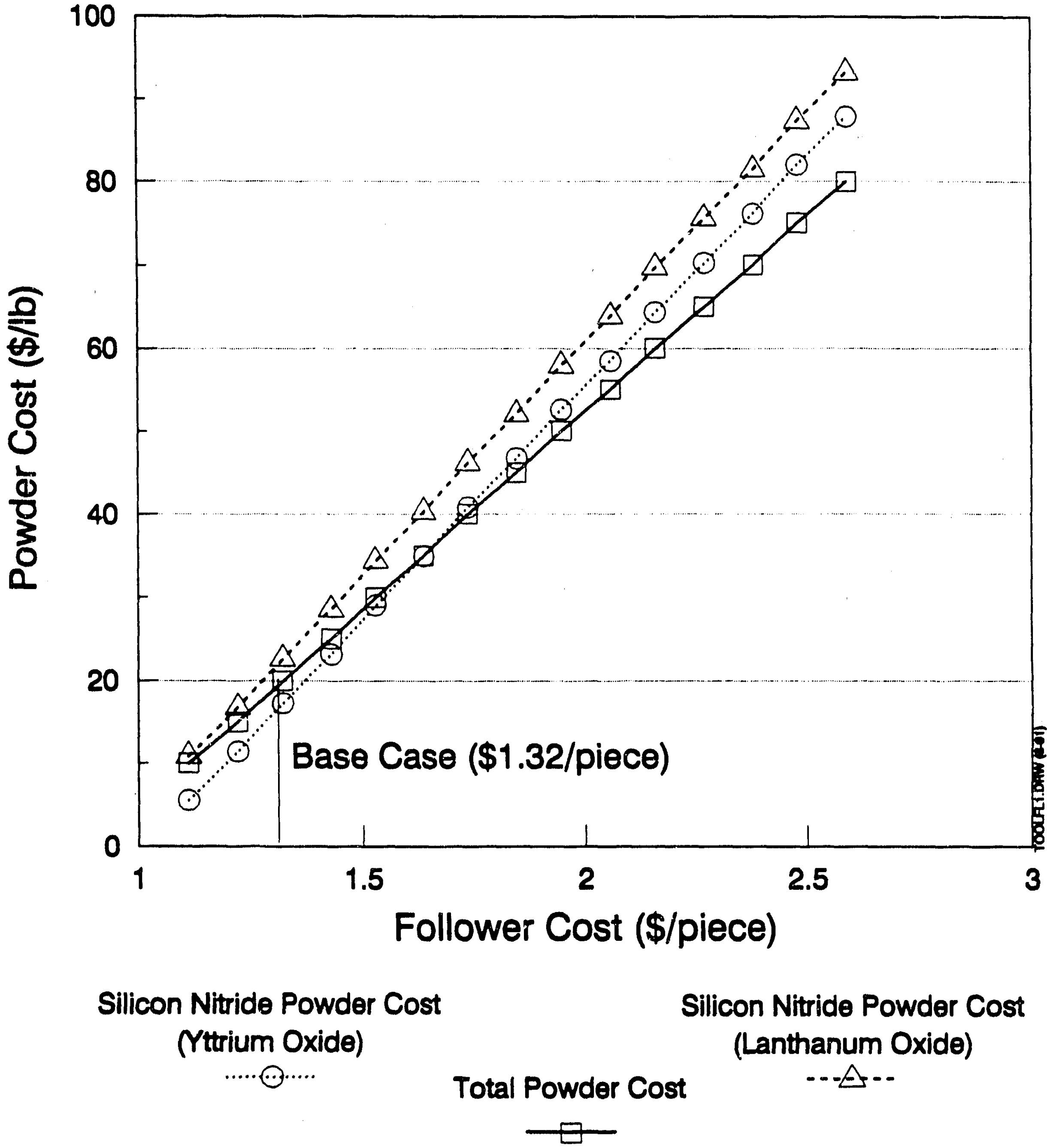


Figure 3.2 Sensitivity of follower cost to changes in powder cost.

Powder Composition : 2% Alumina
13% Yttrium/Lanthanum Oxide
85% Silicon Nitride

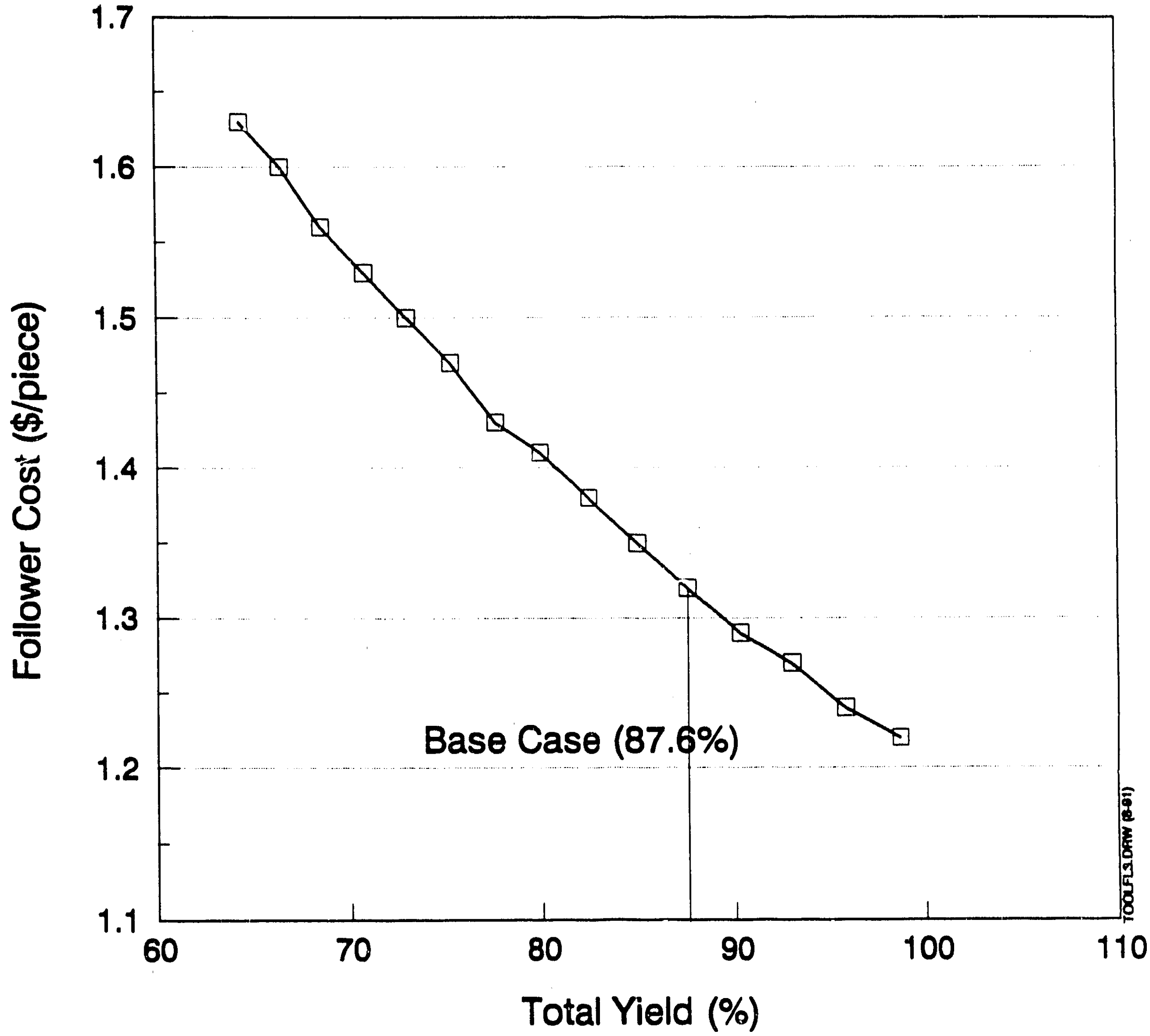


Figure 3.3 Sensitivity of follower cost to changes in total yield.

(Total yield range of 64.4%-98.7% corresponds to Technology Factor of 0.95-1.02 and Grinding Yield of 93.1%-100%)
Silicon Nitride Powder Cost = $17.29/lb (Yttrium Oxide sintering aid)

3.1.2.2 Production Volume vs Follower Cost

The sensitivity of follower cost to the yearly production volume is shown in Figure 3.4. Follower cost is sensitive to production volume, but the sensitivity decreases as production volume increases. At a low production volume of 4.4 million pieces/yr, follower cost is $1.45/piece; the cost decreases by $0.05/piece when the production volume increases by 1.2 million pieces/yr. Follower cost is estimated to be $1.32/piece for the base-case production volume of 10 million pieces/yr.

3.1.2.3 Grinding Rate vs Follower Cost

Near-net shape processing has been advocated for some time in the advanced ceramics industry to cut down on the substantial cost incurred at final finishing. Figure 3.5 illustrates the estimated relationship between roller-follower cost and the grinding rate at final finishing and machining. Follower cost decreases sharply with an increase in grinding rate. An increase in grinding rate of 20 pieces/hr from the base-case value of 30 pieces/hr causes a decrease in base-case follower cost of $0.22/piece from the base-case value of $1.32/piece. A high grinding rate of 100 pieces/hr can bring down the follower cost to less than one dollar (i.e., $0.94/piece).

3.1.3 Powder Cost Reductions in Combination with Other Technical Improvements

The above sensitivity analyses indicate that production costs are most sensitive to changes in total yield and grinding rate. This subsection examines how reductions in powder cost in combination with technology improvements in these parameters that lower cost, could affect the total cost of roller followers. Figure 3.6 illustrates the sensitivity of follower cost to silicon nitride powder cost under three different assumptions about total yield. Note that the difference in follower cost between different total yields becomes larger as the cost of silicon nitride powder increases. For a given silicon nitride powder cost, say $40/lb, the cost of a follower varies between $1.60 and $2.21 per piece as total yield changes correspondingly between 98.7% and 64.4%. Follower cost can be as low as $1.03/piece if total yield is increased to 98.7% and the cost of silicon nitride powder is reduced to $5.53/lb. Unfortunately, model results indicate that this combination of yield improvement and lower powder cost (which reflects optimistic conditions) does not reduce the cost of followers below their metallic counterparts.

The cost of roller followers was found to be highly sensitive to changes in the grinding rate at final finishing and machining. Figure 3.7 illustrates the sensitivity of follower cost to changes in the cost of silicon nitride powder under three different assumptions about the grinding rate at the finishing step. Note that for any given silicon nitride powder cost, the difference in follower cost due to different grinding rates is the same. The model suggests a reduction in follower cost of $0.38/piece with an improvement in the grinding rate from the base-case rate of 30 pieces/hr to 100 pieces/hr. Follower cost reduction is significantly higher (i.e., $0.29/piece) when the grinding rate is increased from 30 pieces/hr to 65 pieces/hr, as compared to $0.09/piece when the grinding rate is increased from 65 pieces/hr to 100 pieces/hr. A grinding rate of 100 pieces/hr and a silicon nitride powder cost of $5.53/lb could yield a follower cost of as low as $0.73/piece. This compares quite favorably to the $0.60/piece cost of existing steel followers with needle bearings.

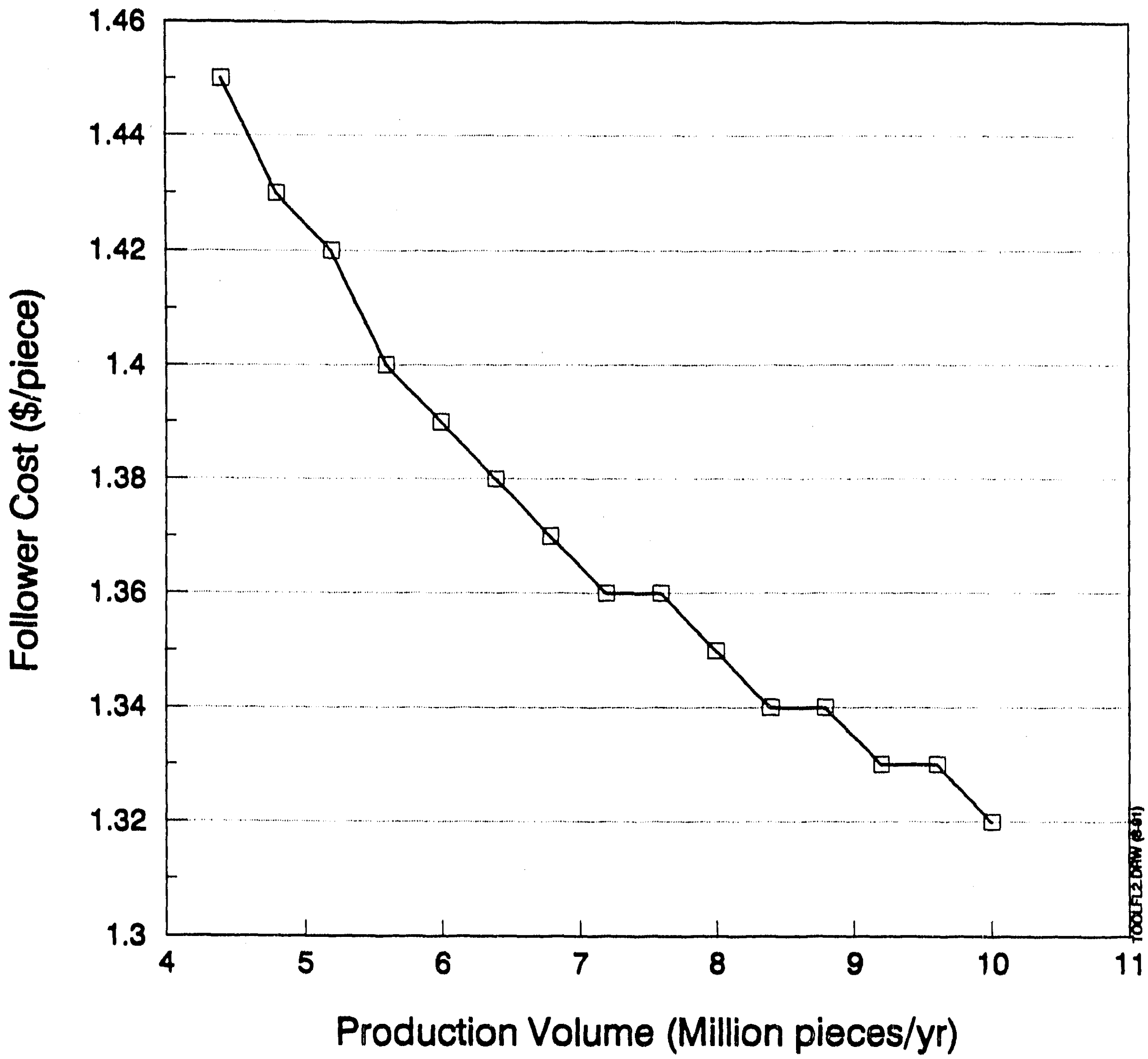


Figure 3.4 Sensitivity of follower cost to changes in production volume.

Silicon Nitride Powder Cost = $17.29/lb
(Yttrium Oxide sintering aid)

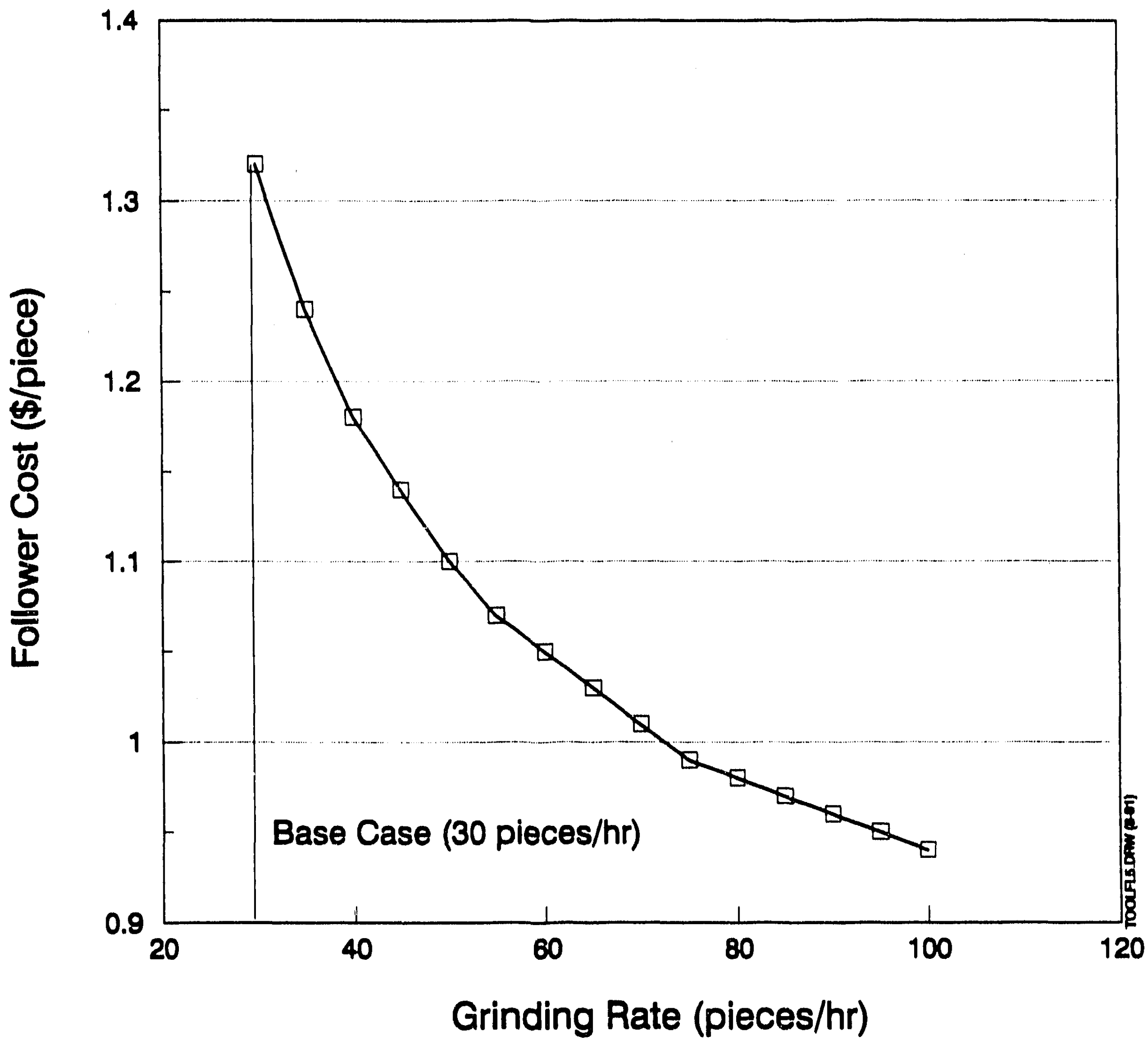


Figure 3.5 Sensitivity of follower cost to changes in grinding rate.

Silicon Nitride Powder Cost = $17.29/lb
(Yttrium Oxide sintering aid)

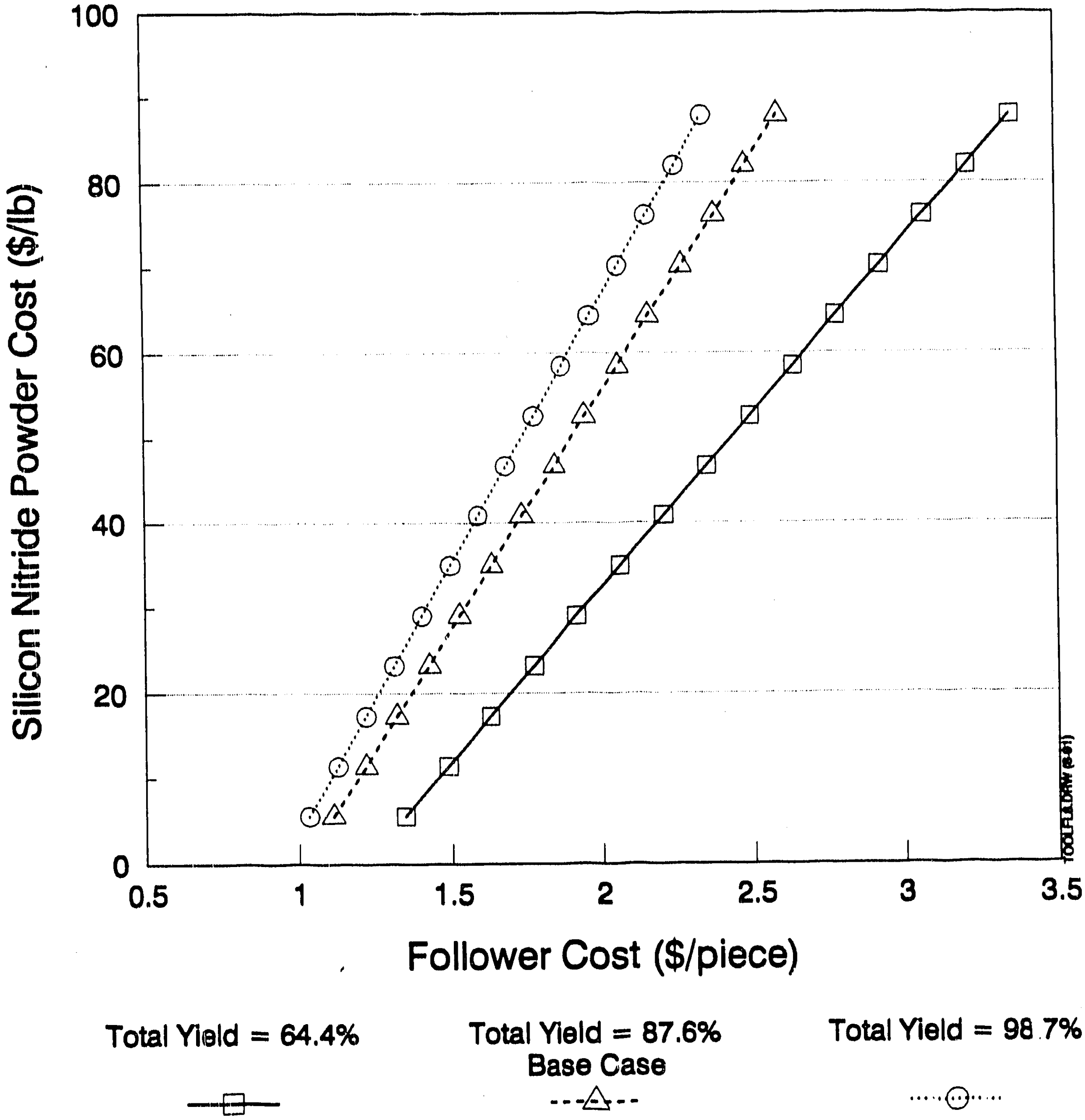


Figure 3.6 Sensitivity of follower cost to changes in silicon nitride powder cost and total yield.

(Assumes powder composition : 2% Alumina @ $5/lb
13% Yttria @ $40/lb and rest 85% Silicon Nitride)

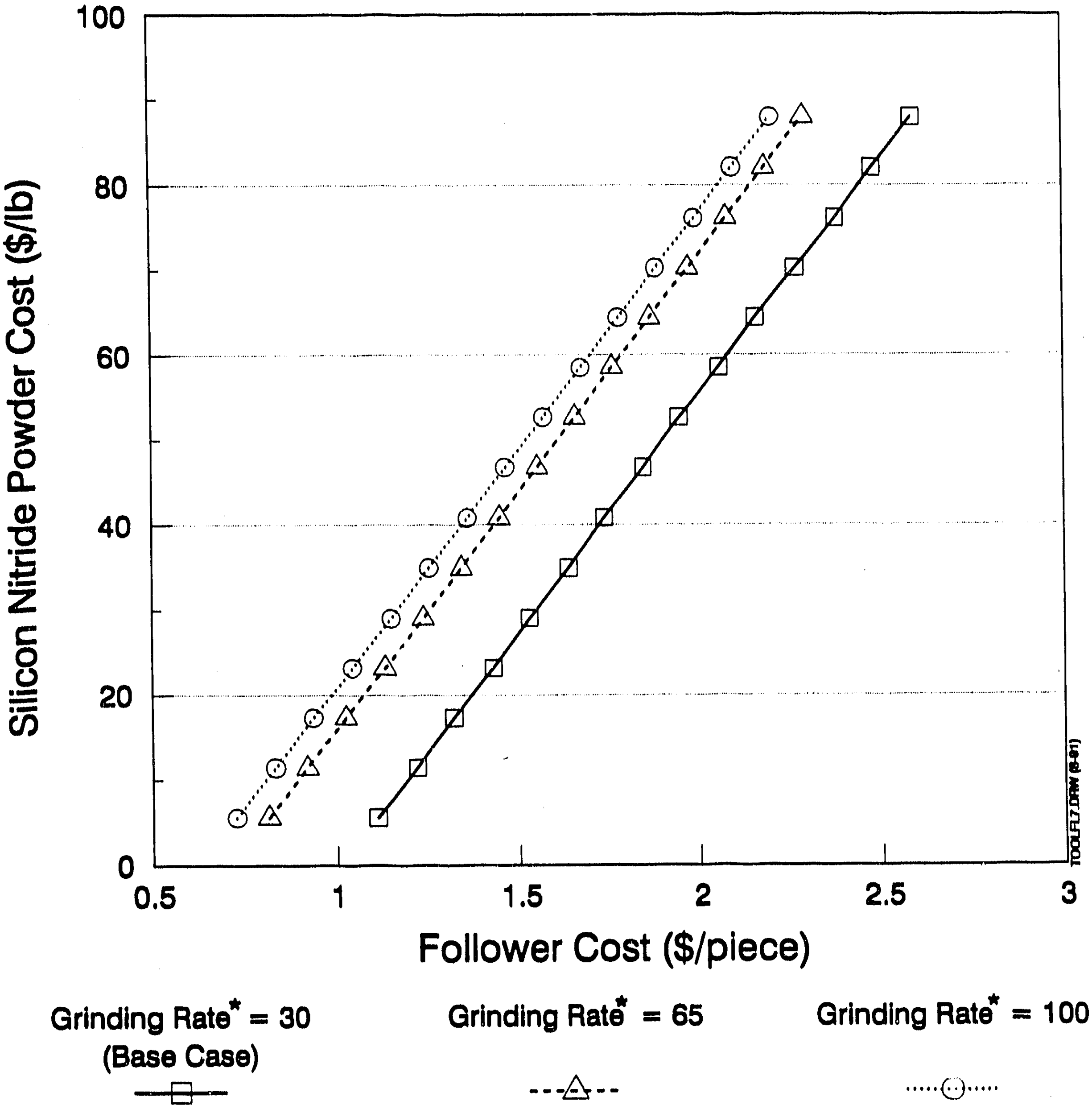


Figure 3.7 Sensitivity of follower cost to changes in silicon nitride powder cost and grinding rate.

(Assumes powder composition : 2% Alumina @ $5/lb
13% Yttria @ $40/lb and rest 85% Silicon Nitride)
*Grinding Rate (pieces/hr)

3.2 Turbocharger Rotors

3.2.1 Base-Case Results

Table 3.2 lists the major base-case assumptions used to estimate the cost of turbocharger rotors using the enhanced MIT turbocharger rotor model. As in the case of roller followers, these assumptions are an optimistic reflection of current or near-term state-of-the-art technology.

Table 3.2 Base-case assumptions for turbocharger rotors

Part Weight	0.62 lbs
Powder Cost (includes sintering aids)	$20/lb
Max. Production Volume	2,000,000 parts/year
Process Step Yields*	
Materials Preparation	95%
Injection Molding	98%
Binder Removal	98%
Sintering	95%
Grinding	98%
Inspection	98%
Total Yield	83%
Binder Removal Time	72 hrs
Sintering	Continuous at 1700° C in N_2 atmosphere
Grinding Rate	3 parts/hr
Labor Cost	$13.50/hr
Total Capital Cost (at Max. Production Volume)	$112 M
Cost of Capital	12%

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

Figure 3.8 gives the estimated base-case cost and its distribution by the major cost components for manufacturing silicon nitride turbocharger rotors. Materials contribute an estimated 46.1% to the total base-case cost of $38.85/piece, the largest of all contributors. Recall that turbocharger rotors made from Inconel 713C superalloy currently cost between $15 and $20 per piece. The major material input other than powder that contributes to materials cost is replacement of injection molding dies. (The wear factor in these dies is high and they need frequent resurfacing). Note that, in addition to powder, materials include wax, binder, mold, grinding wheels, and inert gas.

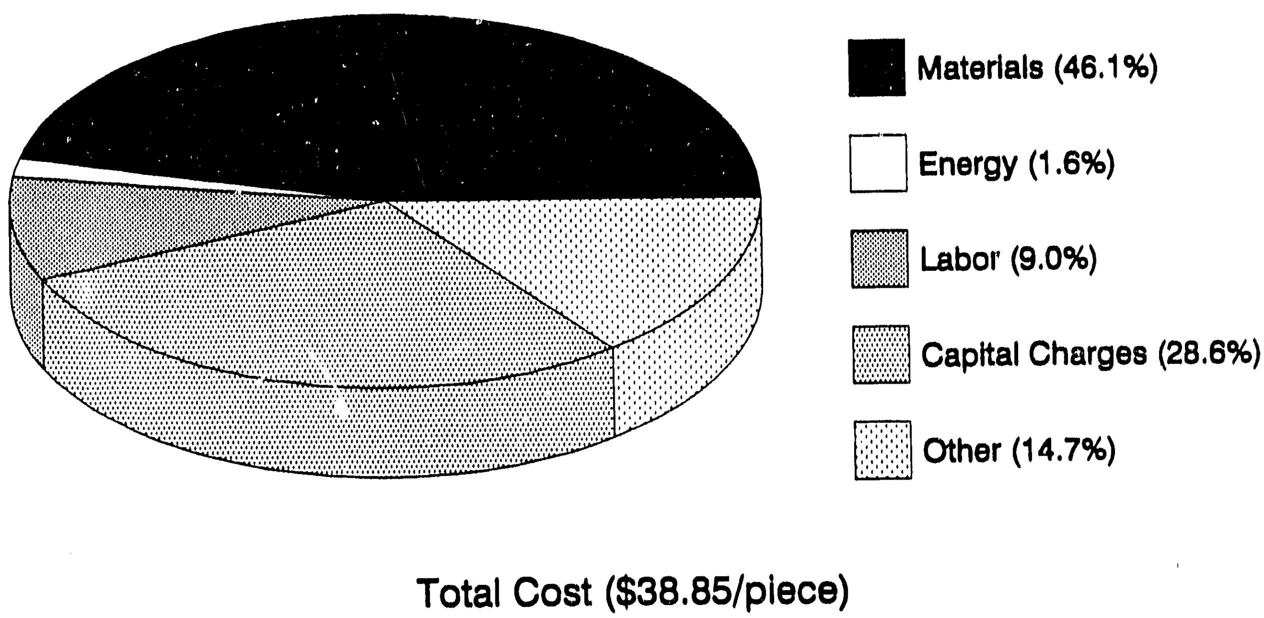


Figure 3.8 Estimated base-case cost of manufacturing silicon nitride turbocharger rotors.

Assumptions: Total Yield : 83%
Powder Cost : $20/lb (Silicon Nitride Powder = $19.02/lb with Yttrium Oxide as sintering aid)
Production Volume : 2 million pieces/yr

TURBOFL1.DRW (12-91)

Another major cost factor is capital. Tooling for the injection molded rotor is complex and expensive, and total capital cost for an annual production volume of 2 million rotors is estimated at $112 million. The "other" cost component includes the high cost of rebuilding continuous furnaces, required every six months, and for elements and thermocouples that may last only a week or two. Labor cost, although not high in terms of percentage of total cost, is significantly higher (i.e., $5.09/piece) than is found in the case of roller followers.

Figure 3.9 illustrates the estimated relationship between the cost of powder and the total cost of manufacturing a ceramic turbocharger rotor. The assumed powder composition in this case is 2% Al_2O_3 + 6% Y_2O_3/La_2O_3 + 92% Si_3N_2. The solid, dotted, and dashed lines are interpreted as in Figure 3.2. Turbocharger cost is estimated to vary linearly from $29.54/piece to $76.09/piece for an increase from $7.50/lb to $70/lb in total powder cost. For any given turbocharger cost, silicon nitride powder cost must be lower when Y_2O_3 is used as a sintering aid as compared to La_2O_3. The former sintering aid is expensive ($40/lb) compared to the cost of the latter sintering aid. For example, with a base-case turbocharger cost of $38.85/piece and a total powder cost of $20/lb, the cost of silicon nitride powder is $21.30/lb when La_2O_3 is used as the sintering aid and is $19.02/lb when Y_2O_3 is used. The difference in turbocharger cost between the two different sintering aids is not sensitive to silicon nitride powder cost. For a given silicon nitride powder cost, a turbocharger costs $1.25 more when Y_2O_3 is used as compared to La_2O_3.

Figure 3.9 indicates that a reduction in silicon nitride powder cost (using Y_2O_3 as the sintering aid) to $5.43/lb could bring down the cost of turbocharger rotors to $29.54/piece, which is 1.5 to 2 times the cost of existing metallic parts. Therefore, our model suggests that lower powder cost will not alone be sufficient to bring about the economic viability of ceramic turbochargers.

3.2.2 Sensitivity Analyses

Our process-cost model was exercised to determine the technology parameters to which total cost is most sensitive. Sensitivity analysis was performed on several technical parameters, including production volume, total yield, capital costs, and grinding rate.

3.2.2.1 Production Volume vs Turbocharger Cost

The sensitivity of turbocharger cost to changes in production volume is summarized in Figure 3.10. At low levels of production volume the cost is very sensitive to changes in output. The cost per turbocharger decreases drastically, i.e., $98.79/piece to $52.73/piece, when the yearly production volume is increased from 100,000 to 600,000. The sensitivity of cost to production volume diminishes greatly as the yearly production volume approaches our assumed maximum capacity limit of 2 million parts, which corresponds to our base-case assumption.

3.2.2.2 Total Yield vs Turbocharger Cost

As discussed earlier, the variation of technology factor is used as the yardstick for the variation of total yield. A technology factor range of 0.91 to 1.02 corresponds to a total yield range of 47.3% to 93.7%. Figure 3.11 illustrates the estimated relationship between total yield and turbocharger cost. Turbocharger cost decreases close to linearly ($0.57/piece) with a 1% increase in total process yield. Under the most optimistic conditions, turbocharger cost can be as low as $35.33/piece when total yield is 93.7%.

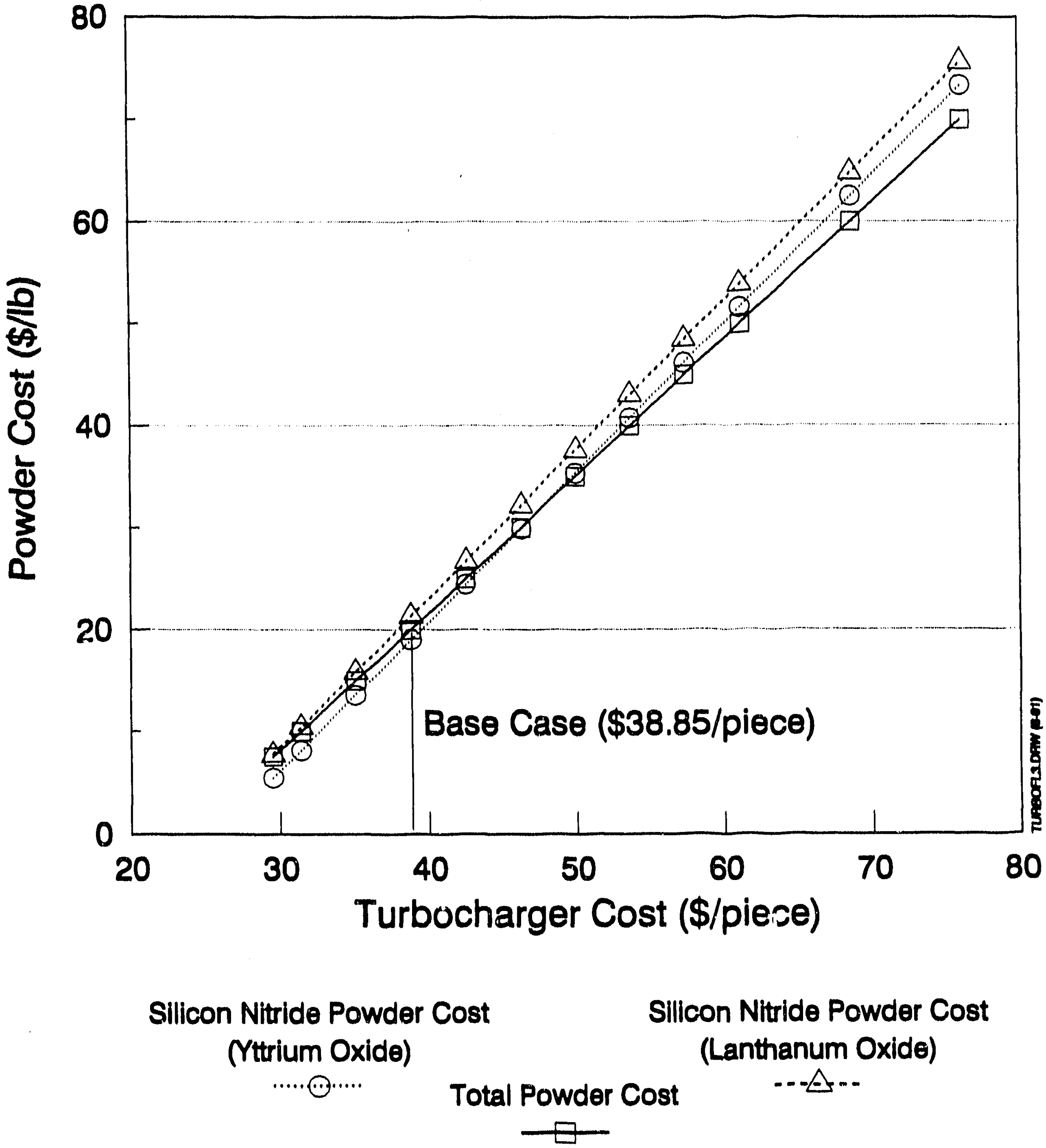


Figure 3.9 Sensitivity of turbocharger cost to changes in powder cost.

Powder Composition :92% Silicon Nitride
2% Alumina
6% Yttrium/Lanthanum Oxide

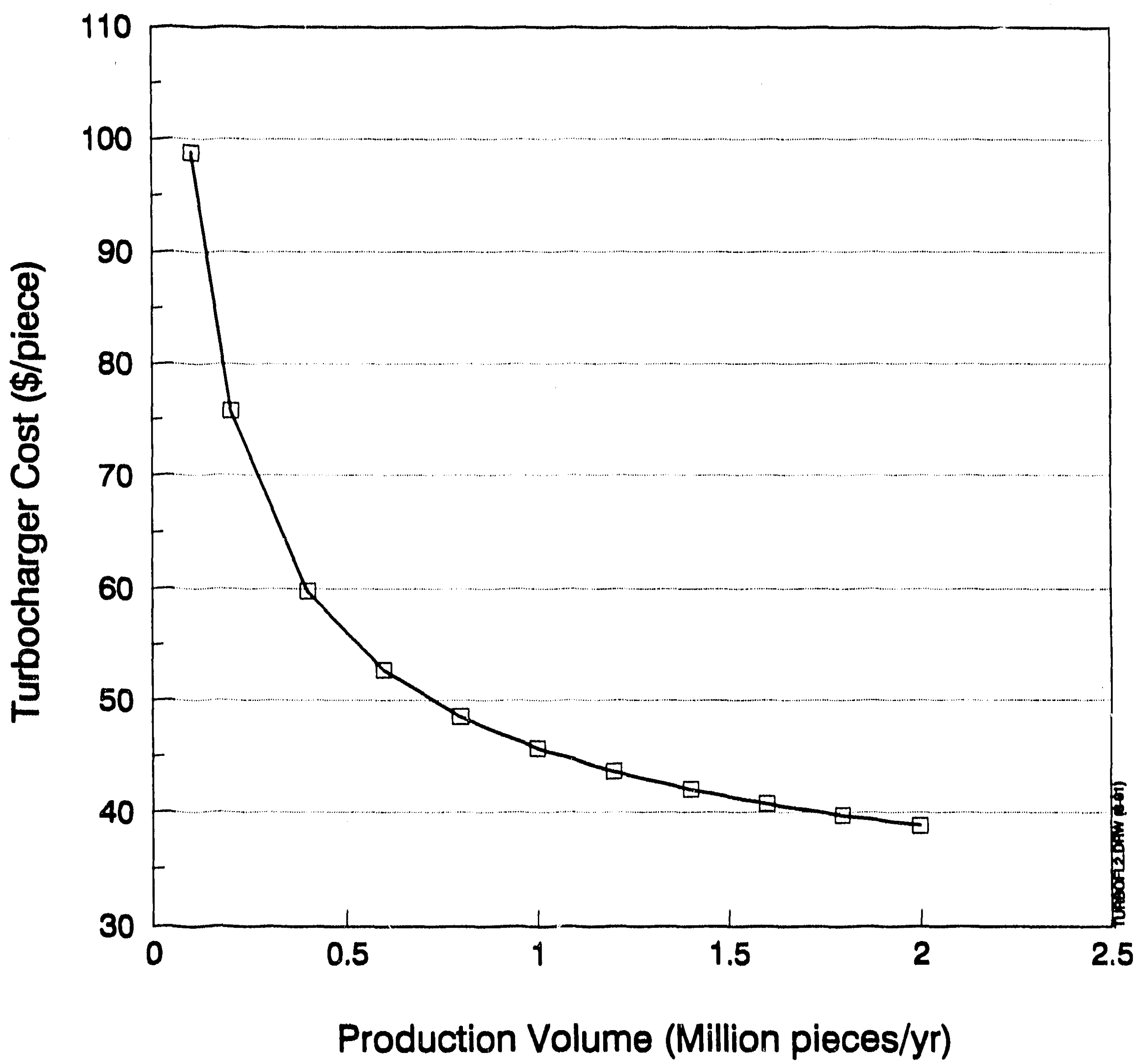


Figure 3.10 Sensitivity of turbocharger cost to changes in production volume.

Silicon Nitride Powder Cost = $19.02/lb
(Yttrium Oxide sintering aid)

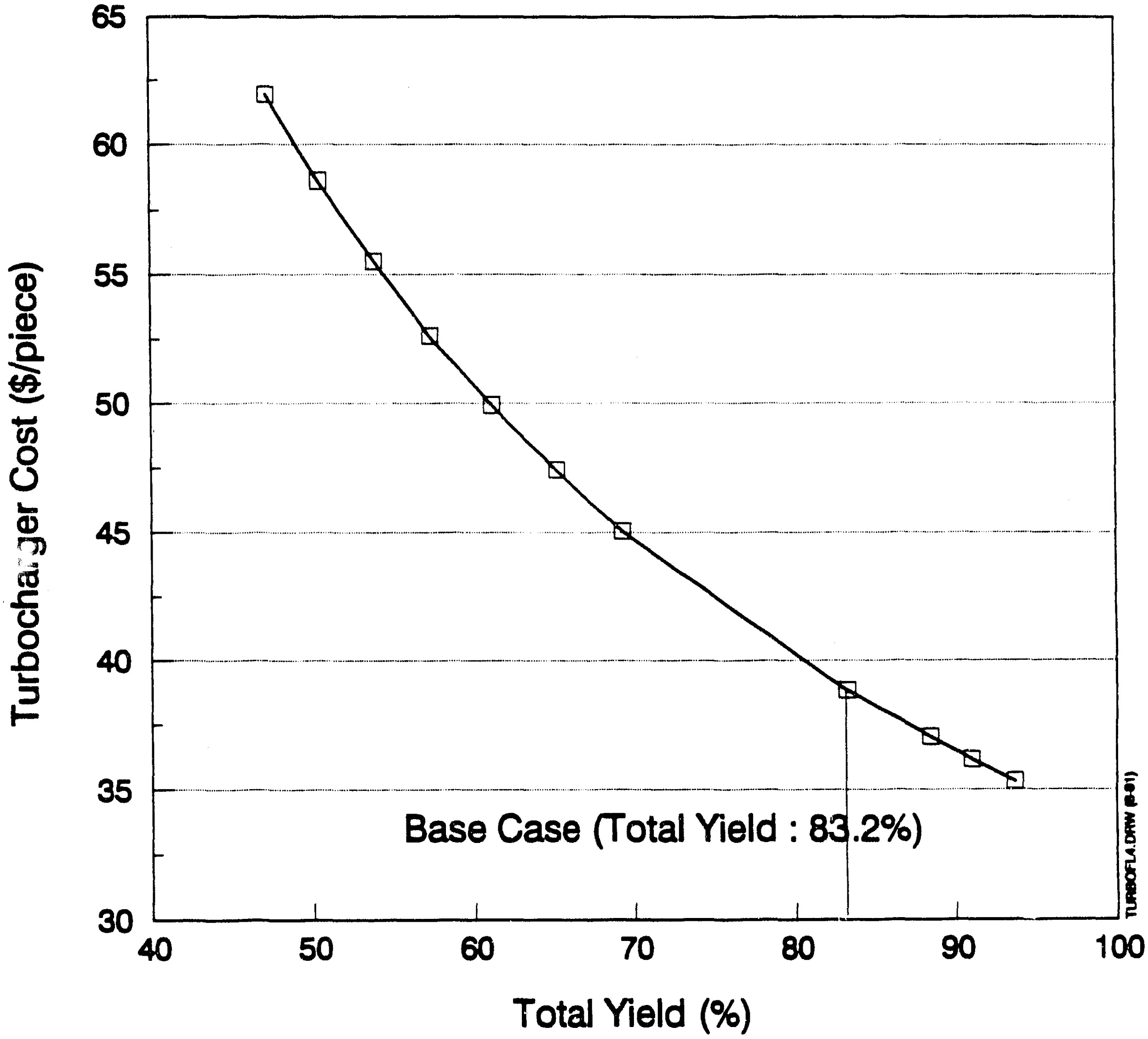


Figure 3.11 Sensitivity of turbocharger cost to changes in total yield.

(Total yield range of 47.3%-93.7% corresponds to Technology factor of 0.91 - 1.02)

Silicon Nitride Powder Cost = $19.02/lb (Yttrium Oxide as sintering aid)

3.2.2.3 Capital Cost vs Turbocharger Cost

The sensitivity of turbocharger cost to percentage changes in the cost of capital at various process steps is summarized in Figure 3.12. Rather than examining the sensitivity of turbocharger cost to the cost of capital at any particular step, Figure 3.12 illustrates how the estimated cost of a turbocharger changes when capital cost changes from the base-case capital cost by some given percentage. A value of 1 corresponds to the capital cost estimate used in the base case. A value of, for example, 0.8 indicates that all capital costs at all production steps equal 80% of the base-case values.

The estimated relationship between turbocharger cost and percentage changes in the cost of capital at the various process steps is linear, and the turbocharger cost increases by 17 cents/piece for every 1% increase in total capital cost. (Recall that total base-case capital cost is estimated to be $112 million for a production volume of 2 million pieces/yr).

3.2.2.4 Grinding Rate vs Turbocharger Cost

The cost of a turbocharger is sensitive to the grinding rate per machine at the final finishing stage, as illustrated in Figure 3.13. The cost of a turbocharger decreases by $1.27/piece (i.e., from $38.85/piece to $37.58/piece) as the grinding rate increases from 3 pieces/hr to 11 pieces/hr. The cost sensitivity is not high, since labor contributes only 9% of total cost, as observed earlier in Figure 3.8.

3.2.3 Powder Cost Reductions in Combination with Other Technical Improvements

The above sensitivity analyses indicate that production cost is most sensitive to changes in total yield and production volume. This subsection examines how reductions in powder cost, in combination with other technology improvements that lower cost, could affect the total cost of turbocharger rotors.

Figure 3.14 illustrates the sensitivity of turbocharger cost to changes in silicon nitride powder cost under three different assumptions about total yield. For a given silicon nitride powder cost of $5.43/lb, turbocharger cost is estimated to vary from $45.55/piece to $27.07/piece as total yield varies from 47.3% to 93.7%. For higher silicon nitride powder costs, turbocharger cost variations become larger for identical variations in total yield. Under very optimistic conditions, turbocharger cost could be reduced to as low as $27.07/piece if the cost of silicon nitride powder is reduced to $5.43/lb and total yield is increased to 93.7%.

The sensitivity of turbocharger cost to variations in silicon nitride powder cost for three different annual production volumes is illustrated in Figure 3.15. For a given silicon nitride powder cost, the estimated variation in turbocharger cost due to changes in yearly production volume is large (e.g., a reduction of $60.13/piece when yearly production volume is increased from one hundred thousand to two million). The difference in turbocharger cost due to different production levels is unaffected by the change in silicon nitride powder cost. Our model suggests that turbocharger cost could be reduced to $29.54/piece if silicon nitride powder cost is reduced to $5.43/lb and production volume reaches 2 million pieces/yr. Production volumes below our base-case value could have a significant impact on the ultimate economic viability of silicon nitride turbocharger rotors.

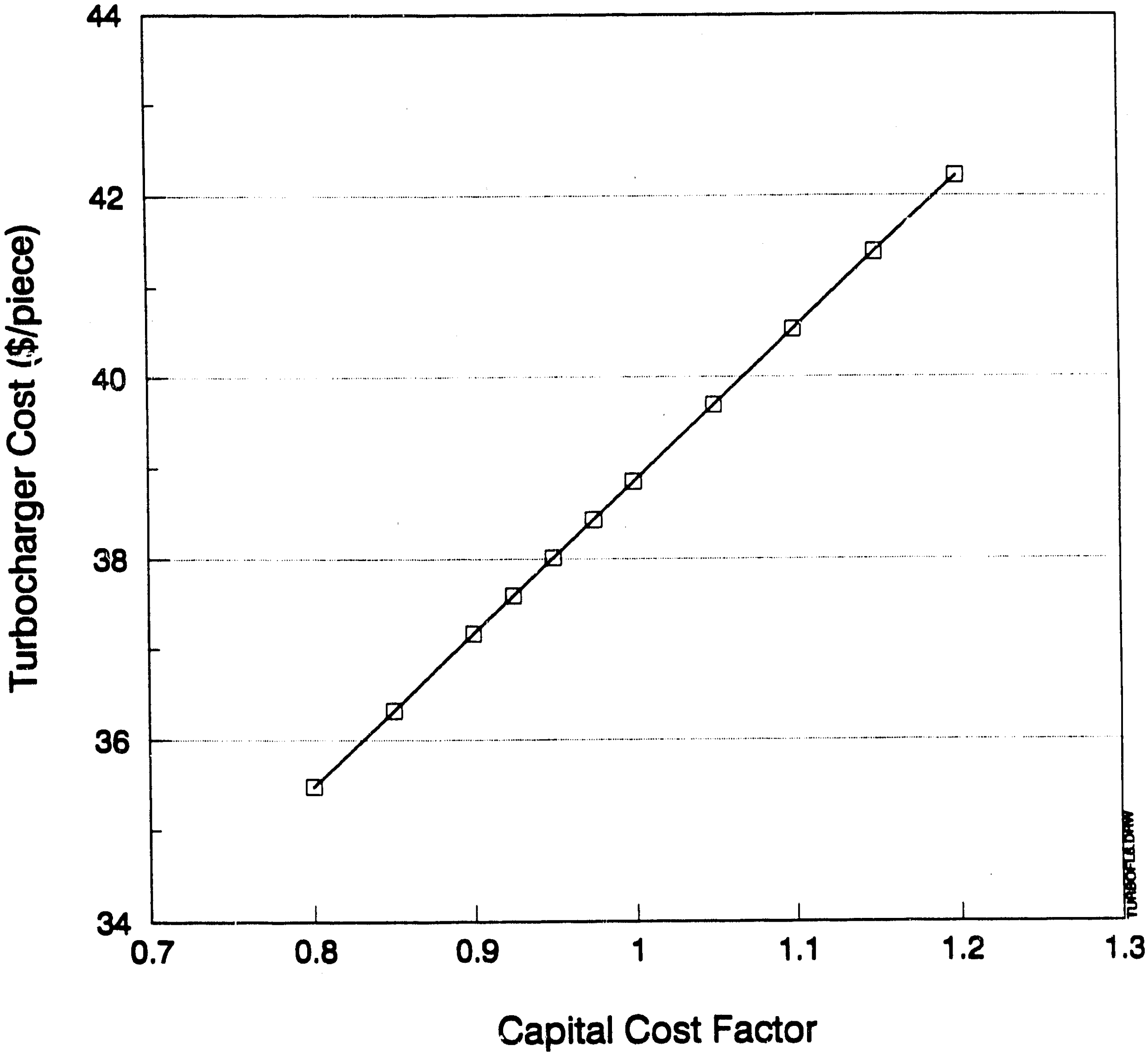


Figure 3.12 Sensitivity of turbocharger cost to changes in capital cost.

(A capital factor of 1 represents base case)
Base Case Total Capital Cost = $ 112M
Silicon Nitride Powder Cost = $19.02/lb
(Yttrium Oxide as sintering aid)

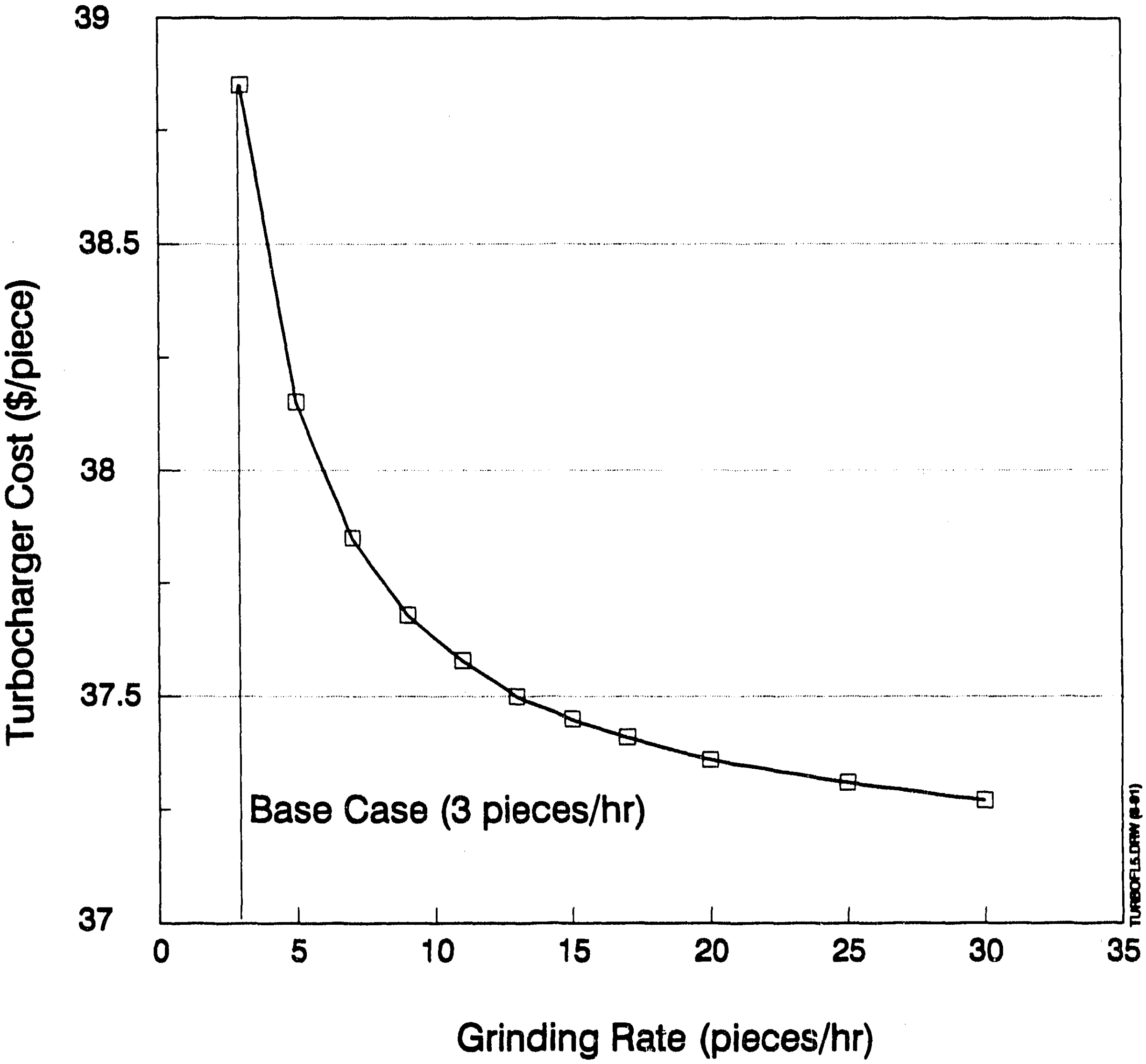


Figure 3.13 Sensitivity of turbocharger cost to changes in grinding rate.

Silicon Nitride Powder Cost = $19.02/lb
(Yttrium Oxide as sintering aid)

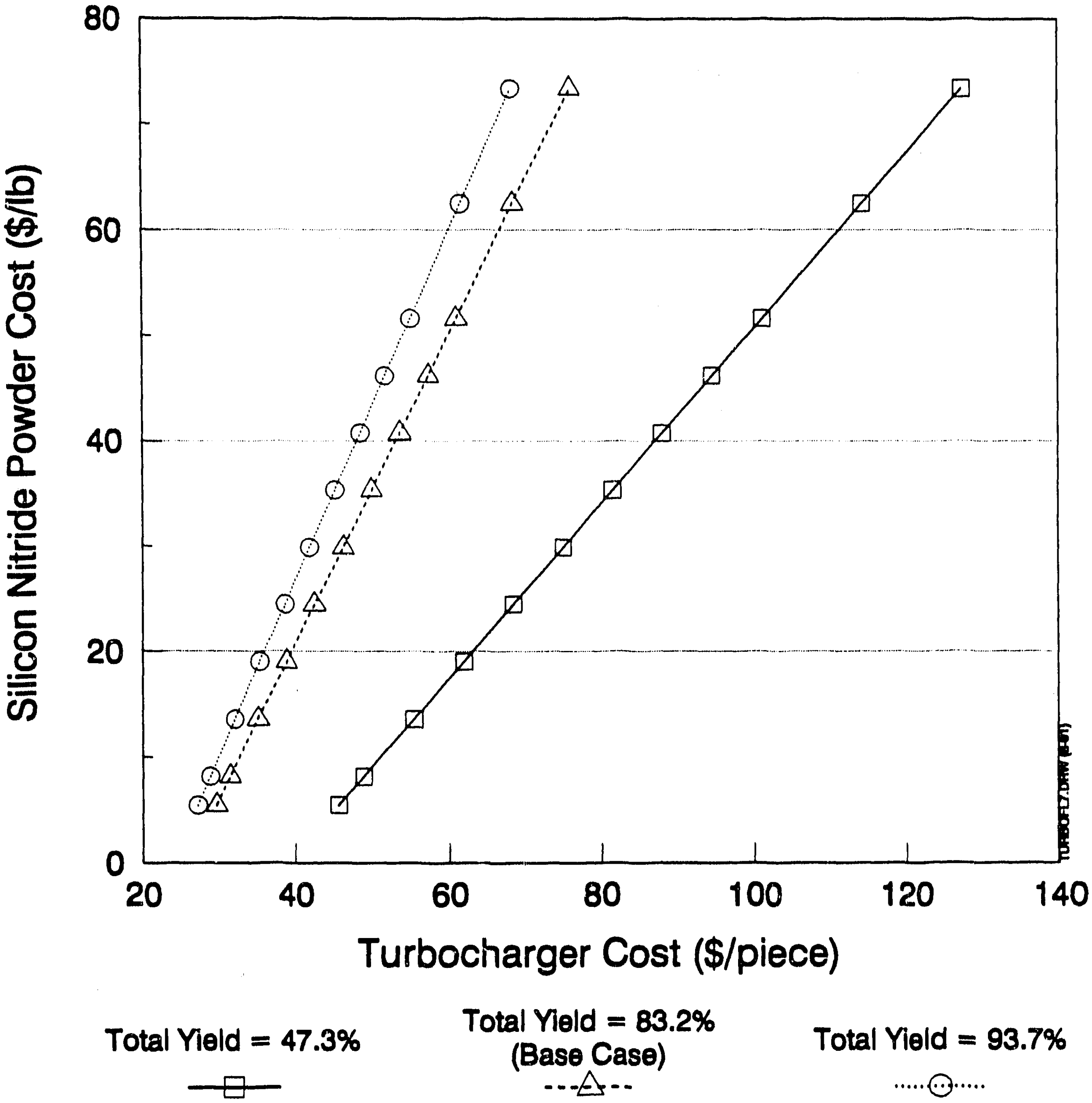


Figure 3.14 Sensitivity of turbocharger cost to changes in silicon nitride powder cost and total yield.

(Assumes powder composition : 2% Alumina @ $5/lb
6% Yttria @ $40/lb and rest 92% Silicon Nitride)

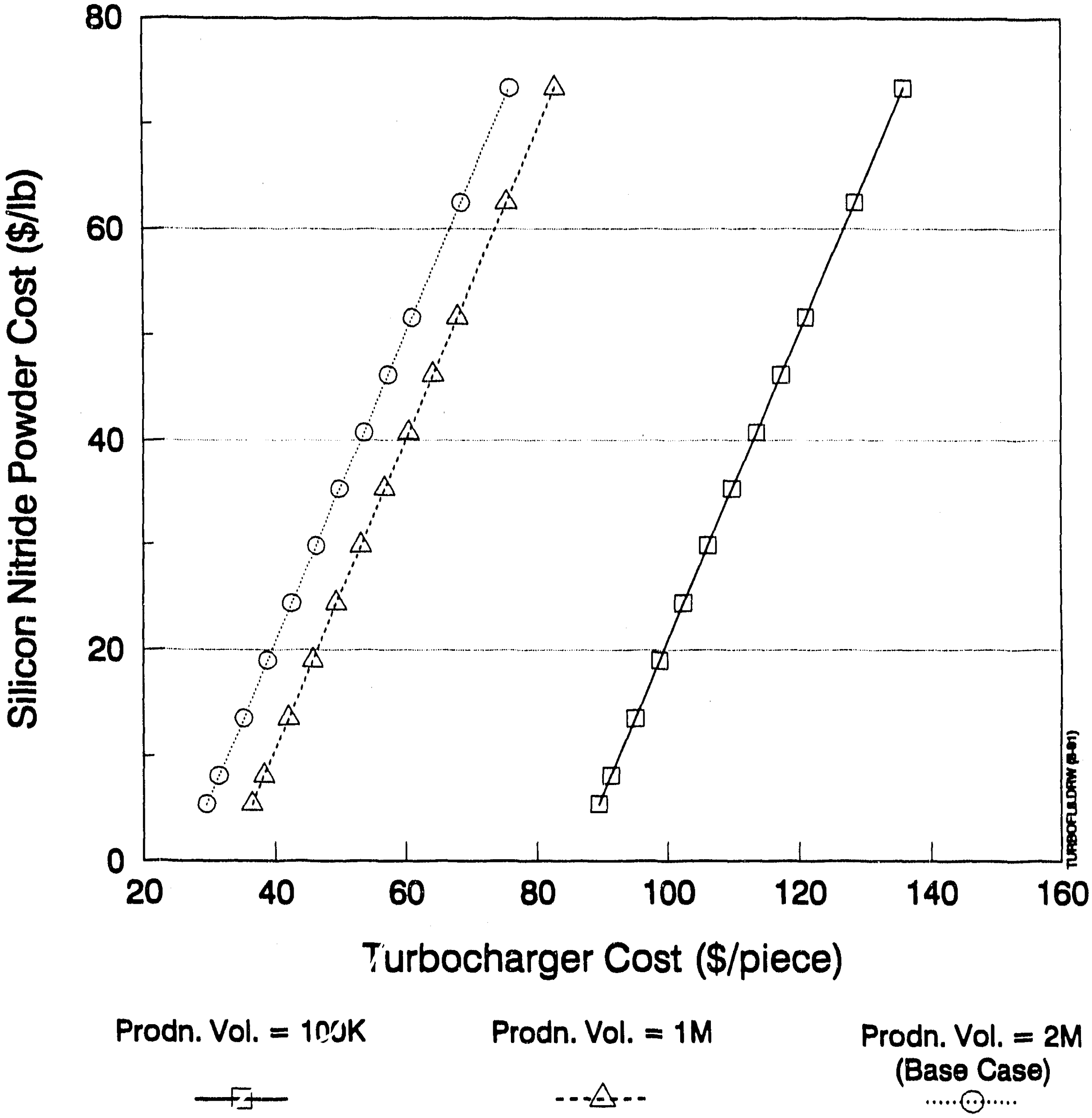


Figure 3.15 Sensitivity of turbocharger cost to changes in silicon nitride powder cost and production volume.

(Assumes powder composition : 2% Alumina @ $5/lb
6% Yttria @ $40/lb and rest 92% Silicon Nitride)

4. CONCLUSIONS

It is widely accepted that the cost of advanced ceramic parts must be reduced if advanced ceramics, such as silicon nitride, are to become a widespread alternative to metallics. Various R&D programs are currently underway to reduce the cost of ceramics, including work to lower the cost of high-quality ceramic powders. High-quality silicon nitride powders currently cost about $20 per pound, although technology improvements are envisioned that could potentially lower that cost to between $5 and $6 per pound.

This work focused on the potential contribution that lower cost powders could make toward improving the economic viability of advanced ceramics. The work focused specifically on silicon nitride and examined two automotive engine parts that are representative of the spectrum of advanced ceramic components -- i.e., roller followers and turbocharger rotors. The cost of an existing steel follower is about $0.60/piece; turbochargers cost between $15-$20 each when made from superalloys. Most industry experts argue that advanced ceramic parts must cost no more than their metallic counterparts and provide comparable quality and reliability if ceramics are to be viable alternatives to metallics.

To examine the potential contributions that lower cost powders could make in reducing the cost of ceramic components, two process-cost models were developed, one for each engine component. A base-case set of input assumptions was formulated which was judged to be an optimistic reflection of current or near-term state-of-the-art technology. The models were then used to estimate the costs of our selected engine components given these state-of-the-art conditions. Silicon nitride powder was assumed to cost $20/lb in the base case.

Our models suggest that under our base-case assumptions, neither roller followers nor turbocharger rotors can be produced at a cost comparable to their metallic counterparts. Roller followers are estimated to cost $1.32 per piece (compared to $0.60 per piece for metallics); turbocharger rotors are estimated to cost $38.85 each (compared to $15-$20 per piece for metallics).

Sensitivity analyses revealed that reductions in the cost of silicon nitride powder from about $20/lb to about $5/lb would promote the economic viability of advanced ceramics, but would not in themselves be sufficient to lower the cost of ceramics below their metallic counterparts. Roller followers were estimated to cost $1.11/piece when the cost of silicon nitride power cost was lowered to $5.53 per pound. Turbocharger rotors were estimated to cost $29.54/piece at the lower powder cost.

The models were also exercised to estimate if reductions in powder cost, in combination with other technology improvements that lower cost, could result in ceramic parts that cost less than similar metallic parts. Work was done to determine the technical parameters to which total part cost is most sensitive. In the case of roller followers, total cost was estimated to be most sensitive to total yield and grinding rate. In the case of turbocharger rotors, total cost was estimated to be most sensitive to total yield and production volume.

Although our sensitivity analyses were reflective of technical improvements that are not foreseeable at this time, the resulting part costs were still higher than similar metallic parts. Significant improvements in the grinding rate, in combination with lower cost powders, were estimated to reduce the cost of roller followers to as low as $0.73/piece. The cost of turbocharger rotors was reduced to as low as $27.07/piece when lower cost powders were combined with significantly higher grinding rates.

Our analysis suggests that if, in fact, advanced ceramic parts must cost no more than their metallic counterparts in order for ceramics to be competitive, the current R&D efforts to lower powder costs will not in themselves be sufficient to establish the economic viability of ceramics. Further analysis suggests that sufficient cost reductions cannot be achieved even when lower-cost powders are combined with other significant technical improvements.

These findings call into question the notion that the cost of ceramic components must not exceed the cost of similar metallic parts. Economic viability will ultimately be decided not on the basis of which part is less costly, but on an assessment of the marginal costs and benefits provided by ceramics and metallics. This analysis did not consider the benefits side of the equation. Our findings on the cost side of the equation suggest that the competitiveness of advanced ceramics will ultimately be decided by our ability to evaluate and communicate the higher benefits that advanced ceramic parts may offer.

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APPENDIX A

MODEL ASSUMPTIONS AND INPUT PARAMETERS FOR THE ROLLER FOLLOWER MODEL

A	A	B	C	D
1				
2	SILICON NITRIDE FOLLOWER FABRICATION MODEL			
3				
4				
5	FACTOR PRICES			
6	==			
7		units	$/unit	
8		---------	---------	
9	==========> ENERGY			
10	Electricity	Kwh*	$0.0525	
11	Natural Gas	Mbtu	$6.50	
12				
13		units	$/unit	
14	==========> MATERIALS	---------	---------	
15	CHOOSE MATERIAL BY NUMBER ====>	4	$20.00	
16	1. Alumina Standard Powder	lbs	$0.73	
17	2. Alumina + TiC Powder	lbs	$2.91	
18	3. SiAlON Powder	lbs	$20.00	
19	4. Silicon Nitride Powder	lbs	$20.00	
20				
21	Water	gals	$0.01	
22	Parrafin Wax	lbs	$0.76	
23	Polystyrene	lbs	$1.05	
24	Other Binders	lbs	$1.00	
25	Diamond Tool Inserts		$7.00	
26	Die Cost		$2,500	
27	Multicavity Die Cost		$3,500	
28	Air	lbs	$0.0001	
29	Ware Support	lbs	$1.00	
30	Inert Gas Atmosphere	lbs	$0.16	
31	Glass Encapsulation	lbs	$0.20	
32	Coolant	gals	$0.20	
33				
34	==========> OTHERS			
35	Labor ($/man-hour)		$13.50	
36	Labor Machining ($/man-hour)		$50.00	
37	Cost of Capital (% of initial investment)		12.0%	
38	Tax Burden (% of physical plant)		1.2%	
39	Insurance (% of physical plant)		1.0%	
40	Maintenance (% of physical plant)		6.0%	
41	Years to Recover Investment		10	
42				
43	==========> SENSITIVITY MULTIPLIERS			
44	Equipment Scaling Factor		0.5	
45				
46	INPUT FACTORS			
47	==			
48	Plant Capacity (pieces/yr)		10000000	
49	Max. Plant Capacity (pieces/yr)		10000000	
50	Part Weight	lbs	0.02	
51	Percent Binder	%	6%	
52	Part Outer Diameter	in	0.7	
53	Part Inner Diameter	in	0.3	
54	Part Volume + 20% For Shrinkage	cu in	0.188	3.09
55	Part Length	in	0.5	
56	Operating Time	days/yr	250	
57	Time Occupied	hr/shft	8	
58	Mixing	lb/hr	15	
59	Mixing Time	hr	2	

A	A	B	C	D
60	Volume of Pressed Parts	parts/hr	1902	
61	Lathe (hand operated)	parts/hr	12	
62	Lathe CNC (tooled)	parts/hr	30.0	
63	Press Volume	parts/hr	380	
64	Inspection	parts/hr	60	
65				
66	Pressing Tool Life	pieces	100000	
67	Tool Life	pieces	1250	
68	Grinding Insert Life	hrs	8	
69	Die Life	parts	100000	
70				
71	ASSUMED PROCESS YIELDS			
72	Note: Ist column values indicate overall yields till that process step			
73	Material Preparation	88%	99%	
74	Pressing	89%	99%	
75	** Not Used ** Green Machining	89%	100%	
76	Binder Removal	89%	98%	
77	Sintering	91%	95%	
78	Grinding	96%	98%	
79	Inspection	98%	98%	
80	Total Yield		88%	
81	INPUT Technology Yield Factor		1	
82	Note: IInd column values indicate yields at the individual process step			
83	BINDER REMOVAL PARAMETERS			
84	Batch Weight	lbs/day	739	
85	Weight of Ware Support	lbs	370	
86	Green Density	gm/cc	1.99	
87	Specific Heat		0.25	
88	Binder Volume (%)		6%	
89	Relative Humidity Entrance		70%	
90	Entrance Air Temperature	C	200	
91	Exit Air Temperature	C	25	
92	Drying Heat Efficiency		80%	
93	Binder Removal Time	hrs	8	
94				
95	CHOOSE FIRING METHOD ====>	2	2	
96	1. Periodic			
97	2.Continuous			
98	** Not Used 3. HIP			
99	** Not Used 4.Sinter/HIP			
100	** Not Used 5. Microwave (2.45 GHZ On=0)		1	
101	FIRING PARAMETERS			
102	Thickness of Insulation	ft	0.75	
103	Time at Temp	hrs	24	
104	Firing Temperature	F	3452	
105	Ambient Temperature	F	81	
106	Firing Heat Efficiency (Tunnel)		60%	
107	Firing Heat Efficiency (Periodic)		40%	
108	Firing Heat Efficiency (HIP)		60%	
109	Firing Heat Efficiency (Micro Wave)		80%	
110	HIPPING PARAMETERS			
111				
112	CHOOSE TEMPERATURE BY NUMBER ==>	2	4%	
113				
114	1. Temperature (C)	1200	3%	
115	2. Temperature (C)	1500	4%	
116	3. Temperature (C)	2000	5%	
117				
118	HIP VESSEL DIMENSIONS			

A	A	B	C	D
119	Diameter	cm	30	
120	Height	cm	45	
121	Volume	cu cm	31809	
122				
123	HIP	cycle/day	1	
124	Encapsulation	lb/cycle	62	
125	Density Of Encapsulant	gm/cc	2.2	
126	Packing Density		40%	
127	Number of Parts/ Volume		3332	
128				
129	MACHINING COST AS A FUNCTION OF MATERIAL REMOVED			
130	(This works for tolerance and near net shape)			
131	INPUT TOLERANCE HERE (#)=====>	3	0%	
132				
133				increas
134		in	mm	%
135		----------	----------	----------
136	1.	0.020	0.508	0
137	2.	0.010	0.254	0
138	3.	0.005	0.127	0
139	4.	0.002	0.051	0
140	5.	0.001	0.025	10
141	6.	0.000	0.013	20
142				
143				
144				
145	A	B	C	D
146				
147				
148				
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177				

MATERIAL PREPARATION

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Turbomill (8 liter vessel)	5	$35,000	$175,000
Spray drier	5	$150,000	$750,000
Materials Handling Equipment	5	$5,000	$25,000
Total ($/plant) =>			$950,000

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Powder	0.02	$20.00	$0.42	$22.82
Other Binder	0.001	$1.05	$0.001	$0.07
Total =>			$0.42	$22.89

==========> ENERGY	UNITS	$/UNIT	$/piece	$/kg
Electricity for blending(kwh)	0.013	$0.0525	$0.001	$0.038
		Total =>	$0.001	$0.038

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.003	$13.50	$0.04	$2.08
Capital Charges		12.0%	$0.019	$1.038
Taxes		1.2%	$0.001	$0.070
Insurance		1.0%	$0.001	$0.059
Maintenance		6.0%	$0.007	$0.352
		Total =>	$0.07	$3.60

==========>COST OF MATERIALS PREPARATION	=>	$0.49	$26.53

COST DISTRIBUTION

Materials	$0.42	86
Energy	$0.00	0
Labor	$0.04	8
Capital Charges	$0.02	4
Other	$0.01	2

cu. cm

ISOPRESSING

EQUIPMENT	UNITS	$/UNIT	$/plant
Isopress	5	$400,000	2.00E+06
Pumping Equipment lbs/hr	5	$9,000	$45,000
Materials Handling Equipment	1	$15,000	$15,000
Total ($/plant) =>			2.06E+06

PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Prepared Powder	1.13	$0.49	$0.49	$26.53
Mold Cost	0.000	$2,500	$0.03	$1.53
Total =>			$0.52	$28.06

ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity for pressing(kwh)	0.003	$0.0525	$0.000	$0.007
Total =>			$0.000	$0.007

OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.0002	$13.50	$0.003	$0.17
Capital Charges		12.0%	$0.041	$2.23
Taxes		1.2%	$0.003	$0.15
Insurance		1.0%	$0.002	$0.13
Maintenance		6.0%	$0.014	$0.76
Total =>			$0.06	$3.43

COST OF ISOPRESSING	=>	$0.09	$4.97
COST AFTER ISOPRESSING	=>	$0.58	$31.50

COST DISTRIBUTION

Materials	$0.45	78
Energy	$0.00	0
Labor	$0.04	7
Capital Charges	$0.06	10
Other	$0.03	5

BINDER REMOVAL

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

	UNITS	$/UNIT	$/plant
Binder Removal System	3	$125,000	$375,000
Materials Handling Equipment	1	$12,000	$12,000
Total ($/plant) =>			$387,000

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

	UNITS	$/UNIT	$/piece	$/lb
Pressed Part	1.1	$0.58	$0.58	$31.50
Atmosphere	0.0002	$0.160	0.000025	$0.0013
Total =>			$0.58	$31.50

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

	UNITS	$/UNIT	$/piece	$/lb
Electricity to Remove Binder (kwh)	0.0005	$0.05	$0.0000	$0.001
Total Using Assumed Drying Efficiency		=>	$0.0000	$0.002

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

			$/piece	$/lb
Direct Labor (man-hours)	0.0003	$13.50	$0.005	$0.245
Capital Charges		12.0%	$0.008	$0.414
Taxes		1.2%	$0.001	$0.028
Insurance		1.0%	$0.000	$0.023
Maintenance		6.0%	$0.003	$0.141
		Total =>	$0.02	$0.85

==========>COST OF BINDER REMOVAL => $0.02 $0.85

==========>COST AFTER BINDER REMOVAL => $0.60 $32.35

COST DISTRIBUTION

Materials	$0.45	75
Energy	$0.00	0
Labor	$0.05	8
Capital Charges	$0.07	11
Other	$0.03	5

FIRING - TUNNEL KILN

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Tunnel Kiln with Cars	1.25	$500,000	$625,000
Materials Handling Equipment	1	$12,000	$12,000
	Total ($/plant) =>		$637,000

Note: A value of "zero" for ($/plant) indicates process not being used.

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Part After Drying	1.1	$0.60	$0.60	$32.4
Inert Gas Atmosphere	0.031	$0.16	$0.0050	$0.268
	Total =>		$0.60	$32.6

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Energy To Heat Insulation (Whr)	1	$0.00005	$0.0001	$0.004
To Evaporate Remaining Binder (Whr)	19	$0.00005	$0.0010	$0.055
To Heat Part (Whr)	5	$0.00005	$0.0003	$0.014
To Heat Batch Support (Whr)	3	$0.00005	$0.0001	$0.007
Soaking Heat (Whr)	56	$0.00005	$0.0029	$0.159
Total Using Assumed Firing Efficiency		=>	$0.0074	$0.399

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.0003	$13.50	$0.005	$0.25
Capital Charges		12.0%	$0.013	$0.68
Taxes		1.2%	$0.001	$0.05
Insurance		1.0%	$0.001	$0.04
Maintenance		6.0%	$0.004	$0.23
		Total =>	$0.02	$1.24

		$/piece	$/lb
==========>COST OF FIRING	=>	$0.04	$1.91
==========>COST AFTER FIRING	=>	$0.63	$34.26

COST DISTRIBUTION

Materials	$0.46	72
Energy	$0.01	1
Labor	$0.05	8
Capital Charges	$0.08	13
Other	$0.04	6

Y	Z	AA	AB	AC
FIRING - PERIODIC KILN	for firing option 1 and 4, only			
==========> EQUIPMENT	UNITS	$/UNIT	$/plant	
Periodic Kiln	5	$250,000	0.00E+00	
Materials Handling Equipment	1	$12,000	$0	
			=========	
	Total ($/plant) =>		0.00E+00	
Note: A value of "zero" for ($/plant) indicates process not being used.				
==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Part After Drying	1.1	$0.60	$0.00	$0.00
Inert Gas Atmosphere	0.0310	$0.16	$0.0000	$0.000
			========	========
	Total =>		$0.00	$0.0
==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Energy To Heat Insulation (Whr)	1	$0.00005	$0.0000	$0.000
To Evaporate Remaining Binder (Whr)	19	$0.00005	$0.0000	$0.000
To Heat Part (Whr)	5	$0.00005	$0.0000	$0.000
To Heat Batch Support (Whr)	3	$0.00005	$0.0000	$0.000
Soaking Heat (Whr)	56	$0.00005	$0.0000	$0.000
			========	========
Total Using Assumed Firing Efficiency		=>	$0.000	$0.000
==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.0003	$13.50	$0.000	$0.000
Capital Charges		12.0%	$0.000	$0.00
Taxes		1.2%	$0.000	$0.000
Insurance		1.0%	$0.000	$0.000
Maintenance		6.0%	$0.000	$0.00
			========	========
		Total =>	$0.00	$0.00
==========>COST OF FIRING		=>	$0.00	$0.00
==========>COST AFTER FIRING		=>	$0.00	$0.0
COST DISTRIBUTION				
Materials			$0.00	0
Energy			$0.00	0
Labor			$0.00	0
Capital Charges			$0.00	0
Other			$0.00	0

MACHINE SHOP

o

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Lathes	73	$35,000	2.56E+06
Special Chucks	8	$5,000	$40,000
Tooling Crane	1	$15,000	$15,000
Benches and Cabinet	8	$625	$5,000
Miscellaneous Tools	1	$10,000	$10,000
	Total ($/plant) =>		2.63E+06

====> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Fired Part	1.10	$0.63	$0.63	$34.26
Coolant	0.01	$0.20	$0.00	$0.12
Grinding Wheels	0.00	$7.00	$0.03	$1.73
	Total =>		$0.67	$36.11

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	0.389	$0.0525	$0.020	$1.105
		Total =>	$0.020	$1.105

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.037	$13.50	$0.49	$26.68
Capital Charges		12.0%	$0.051	$2.755
Taxes		1.2%	$0.003	$0.187
Insurance		1.0%	$0.003	$0.156
Maintenance		6.0%	$0.017	$0.934
		Total =>	$0.57	$30.72

==========>COST OF MACHINING		=>	$0.62	$33.67
==========>COST AFTER MACHINING		=>	$1.26	$67.93

COST DISTRIBUTION

Materials	$0.49	39
Energy	$0.03	2
Labor	$0.54	43
Capital Charges	$0.13	10
Other	$0.06	5

QUALITY CONTROL AND STORAGE

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Ultrasonic Testers	36	$25,000	9.00E+05
Special Tables, Jigs, and Other Miscellaneous Equipment	10	$11,600	$116,000
Storage Racks(30discs/rack)	10	$1,000	$10,000
Total ($/plant) =>			1.03E+06

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Machined Parts	1.04	$1.26	$1.26	$67.93
Total =>			$1.26	$67.93

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	0.005	$0.0525	$0.000	$0.015
		Total =>	$0.000	$0.015

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.003	$13.50	$0.04	$2.03
Capital Charges		12.0%	$0.0189	$1.023
Taxes		1.2%	$0.0013	$0.0694
Insurance		1.0%	$0.0011	$0.0578
Maintenance		6.0%	$0.0064	$0.347
		Total =>	$0.07	$3.52

		$/piece	$/lb
==========>COST OF QUALITY CONTROL	=>	$0.07	$3.54
==========>COST AFTER QUALITY CONTROL	=>	$1.32	$71.47

COST DISTRIBUTION

Materials	$0.49	37
Energy	$0.03	2
Labor	$0.58	44
Capital Charges	$0.15	11
Other	$0.07	5

TOTALS Silicon Nitride Roller Follower

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

	$/lb	percent
Material Preparation	$26.53	37.12%
Pressing	$4.97	6.95%
Binder Removal	$0.85	1.20%
Firing	$1.91	2.67%
Finishing	$33.67	47.11%
Inspection	$3.54	4.95%
Total =>	$71.47	100.00%

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

	$/piece	$/lb	Percent
Materials	$0.49	$26.54	37.1
Energy	$0.03	$1.57	2.2
Labor	$0.58	$31.45	44.0
Capital Charges	$0.15	$8.14	11.4
Other	$0.07	$3.77	5.3
Total ========>	$1.32	$71.47	

$/kg ====> $157.23

ASSUMPTIONS

Powder Cost ($/lb)	$20.00
Firing Method	2
Firing Temperature (F)	3452
Hipping Temperature (C)	1500
Machining Tolerance	0.005
Total Yield	88%
Production Volume (pc/yr)	1.00E+07

Materials	$0.49	$26.54	37.1
Capital Charges	$0.15	$8.14	11.4
Energy	$0.03	$1.57	2.2
Labor	$0.58	$31.45	44.0
Other	$0.07	$3.77	5.3

APPENDIX B

MODEL ASSUMPTIONS AND INPUT PARAMETERS FOR THE TURBOCHARGER ROTOR MODEL

INJECTION MOLDING MODEL - Turbo rotors

FACTOR PRICES

A	B	C
	units	$/unit
==========> ENERGY		
ENTER ELECTRICITY COST HERE ====>	Kwh*	$0.0525
Electricity	Kwh*	$0.0525
Natural Gas	Mbtu	$6.50
Light Oil	gal*	$0.97
	units	$/unit
==========> MATERIALS		
CHOOSE MATERIAL BY NUMBER ====>	5	$20.00
1. SiC Standard Powder	lbs	$1.32
2. SiC Submicron powder	lbs	$10.00
3. Alumina Standard Powder	lbs	$0.73
4.Alumina Submicron Powder	lbs	$11.00
5. Silicon Nitride Powder	lbs	$20.00
Water	gals	$0.01
Parrafin Wax	lbs	$0.76
Polystyrene	lbs	$1.05
Other Binders	lbs	$1.00
Diamond Tool Inserts		$7.00
INSERT TOOLING COST IF KNOWN ==>		$0
Injection Molding Tooling (>1000 parts)		$179,247
Air	lbs	$0.0001
Ware Support	lbs	$1.00
Inert Gas Atmosphere	lbs	$0.01
Glass Encapsulation	lbs	$1.00
Coolant	gals	$0.20
==========> OTHERS		
Labor ($/man-hour)		$13.50
Cost of Capital (% of initial investment)		12.0%
Tax Burden (% of operating expenses)		1.2%
Insurance (% of physical plant)		1.0%
Maintenance (% of physical plant)		6.0%
Years to Recover Investment		10

SENSITIVITY MULTIPLIERS

A	B	C
Equipment		0.5
Fuel Energy		1
Electric Energy		1
Raw Materials		1

INPUT FACTORS

A	B	C
Plant Capacity (pieces/yr)		2000000
Maxm. Plant Capacity (pieces/yr)		2000000
Part Weight	lbs	0.62
Percent Wax		30%

A	A	B	C	D
60	Percent Plastics		8%	
61				
62	Tool Life	pieces	100000	
63	Geometric Factor(1=simple,2=medium,3=complex)	3	4.4	
64	Difficulty Factor - Function of Weight		1	
65	Grinding Insert Life	hrs	8	
66				
67	VOLUMES			
68	==			
69	Volume of Parts		20000	
70	Mixing	lb/hr	19	
71	Mixing Time	hr	6	
72	Injection Molding Cycle Time	sec/lb	179	
73	Lathe (hand operated)	parts/hr	12	
74	Lathe CNC (tooled)	parts/hr	3.0	
75	Inspection	parts/hr	60	
76				
77	ASSUMED PROCESS YIELDS			
78	Material Usage		95%	
79	** Not Used ** Parts Volume			
80	Over		99%	
81	Injection Molding	88%	98%	
82	** Not Used ** Green Machining	89%	100%	
83	Binder Removal	89%	98%	
84	Sintering	91%	95%	
85	Grinding	96%	98%	
86	Inspection	98%	98%	
87	Total Yield		83%	
88	Technology Yield Factor (1 to 9)	8	1	
89	INPUT FACTORS			
90	==			
91	BINDER REMOVAL PARAMETERS			
92	Batch Weight	lbs/day	9610	
93	Weight of Ware Support	lbs	4805	
94	Green Density	gm/cc	2.05	
95	Specific Heat		0.25	
96	Binder Volume (%)		38%	
97	Relative Humidity Entrance		70%	
98	Entrance Air Temperature	F	392	
99	Exit Air Temperature	F	77	
100	Drying Heat Efficiency		80%	
101	Binder Removal Time	hrs	72	
102	CHOOSE BINDER REMOVAL TIME ==>	hrs		
103	Molding Temperature	F	230	
104	FIRING PARAMETERS			
105	Thickness of Insulation	ft.	0.75	
106	Time at Temp.	hrs	24	
107	Firing Temperature	F	3092	
108	Ambient Temperature	F	81	
109	Firing Heat Efficiency (Continuous)		60%	
110	Firing Heat Efficiency (Periodic)		40%	
111	Firing Heat Efficiency (HIP)		70%	
112				
113	CHOOSE FIRING METHOD ====>	2	2	
114	1. Periodic			
115	2.Continuous			
116	*** Not Used *** 3. HIP			
117				
118	MACHINING COST AS A FUNCTION OF TOLERANCE			

A	B	C	D
INPUT TOLERANCE HERE (#)=====>	1	20%	
Material Removed	cu in	0.40	
			increas
	in	mm	%
1.	0.02	0.508	20
2.	0.01	0.254	40
3.	0.005	0.127	80
4.	0.002	0.051	140
5.	0.001	0.025	200
6.	0.0005	0.013	360

OPTIONAL STAGES (off=0/on=1)

Green Machining	0	0
Final Finishing	1	1

* Final Finishing includes flash sprue removal *

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MATERIAL PREPARATION

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

	UNITS	$/UNIT	$/plant
Mixers lbs/hr	24	$50,000	1.20E+06
Materials Handling Equipment	24	$10,000	$240,000
Total ($/plant) =>			1.44E+06

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

	UNITS	$/UNIT	$/piece	$/lb
Powder	0.74	$20.00	$14.90	$24.03
Parafin Wax	0.223	$0.76	$0.170	$0.27
Other Binder	0.060	$1.05	$0.063	$0.10
Total =>			$15.13	$24.40

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

	UNITS	$/UNIT	$/piece	$/lb
Electricity for blending(kwh)	0.546	$0.0525	$0.029	$0.046
Total =>			$0.029	$0.046

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

			$/piece	$/lb
Direct Labor (man-hours)	0.117	$13.50	$1.58	$2.55
Capital Charges		12.0%	$0.15	$0.25
Taxes		1.2%	$0.01	$0.01
Insurance		1.0%	$0.01	$0.01
Maintenance		6.0%	$0.05	$0.08
Total =>			$1.80	$2.91

==========>COST OF MATERIALS PREPARATION => $16.96 $27.35

COST DISTRIBUTION

Materials	$15.13	89
Energy	$0.03	0
Labor	$1.58	9
Capital Charges	$0.15	1
Other	$0.07	0

INJECTION MOLDING

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

	UNITS	$/UNIT	$/plant
Injection Molding Unit	67	$750,000	5.03E+07
Materials Handling Equipment	67	$10,000	$670,000
Total ($/plant) =>			5.09E+07

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

	UNITS	$/UNIT	$/piece	$/lb
Prepared Powder	1.14	$16.96	$16.96	$27.35
Mold Type Function of Volume	0.000	$179,247	$2.05	$3.30
Total =>			$19.00	$30.65

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

	UNITS	$/UNIT	$/piece	$/lb
Electricity for Injecting(kwh)	0.198	$0.0525	$0.010	$0.017
Electricity for Heating(kwh)	0.007	$0.0525	$0.000	$0.001
Total =>			$0.010	$0.017

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

			$/piece	$/lb
Direct Labor (man-hours)	0.019	$13.50	$0.25	$0.40
Capital Charges		12.0%	$5.14	$8.29
Taxes		1.2%	$0.31	$0.49
Insurance		1.0%	$0.25	$0.41
Maintenance		6.0%	$1.74	$2.81
Total =>			$7.70	$12.41

		$/piece	$/lb
==========>COST OF INJECTION MOLDING	=>	$9.75	$15.73
==========>COST AFTER INJECTION MOLDING	=>	$26.71	$43.08

COST DISTRIBUTION

Materials	$17.17	64
Energy	$0.04	0
Labor	$1.83	7
Capital Charges	$5.30	20
Other	$2.37	9

BINDER REMOVAL

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Binder Removal System	80	$375,000	3.00E+07
Materials Handling Equipment	80	$5,000	$400,000
Total ($/plant) =>			3.04E+07

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Part After Green Machining	1.12	$26.71	$26.71	$43.08
Atmosphere	56.7	$0.010	$0.352	$0.91
Total =>			$27.06	$44.00

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity to Remove Binder(kwh)	27149	$0.05	$0.09	$0.15
Total Using Assumed Drying Efficiency		=>	$0.11	$0.185

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.003	$13.50	$0.04	$0.06
Capital Charges		12.0%	$3.01	$4.85
Taxes		1.2%	$0.18	$0.29
Insurance		1.0%	$0.00	$0.00
Maintenance		6.0%	$1.02	$1.65
		Total =>	$4.25	$6.85

==========>COST OF BINDER REMOVAL	=>	$7.88	$12.70
==========>COST AFTER BINDER REMOVAL	=>	$31.42	$50.68

COST DISTRIBUTION

Materials	$17.53	56
Energy	$0.15	0
Labor	$1.87	6
Capital Charges	$8.30	26
Other	$3.57	11

FIRING - CONTINUOUS

Y	Z	AA	AB	AC
==========> EQUIPMENT	UNITS	$/UNIT	$/plant	
Tunnel Kiln with Cars	40	$500,000	2.00E+07	
Materials Handling Equipment	40	$12,000	$480,000	
	Total ($/plant) =>		2.05E+07	
==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Part After Drying	1.10	$31.42	$31.42	$50.68
Inert Gas Atmosphere	100066	$0.01	$0.065	$0.10
	Total =>		$31.49	$50.79
==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Energy To Heat Insulation (Whr)	248221	$0.00005	$0.0008	$0.001
To Evaporate Remaining Binder (Whr)	57283986	$0.00005	$0.1940	$0.313
To Heat Batch (Whr)	2323479	$0.00005	$0.0079	$0.013
To Heat Batch Support (Whr)	1161740	$0.00005	$0.0039	$0.006
Soaking Heat (Whr)	11189768	$0.00005	$0.0379	$0.061
Total Using Assumed Firing Efficiency		=>	$0.4076	$0.657
==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.001	$13.50	$0.01	$0.02
Capital Charges		12.0%	$1.99	$3.20
Taxes		1.2%	$0.12	$0.20
Insurance		1.0%	$0.00	$0.00
Maintenance		15.0%	$1.68	$2.72
		Total =>	$3.80	$6.14
==========>COST OF FIRING		=>	$4.28	$6.90
==========>COST AFTER FIRING		=>	$35.70	$57.58
COST DISTRIBUTION				
Materials			$17.59	49
Energy			$0.56	2
Labor			$1.88	5
Capital Charges			$10.29	29
Other			$5.38	15

FIRING - PERIODIC

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Periodic Kiln	80	1.00E+06	8.00E+07
Materials Handling Equipment	80	$12,000	$960,000
	Total ($/plant) =>		8.10E+07

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Part After Drying	1.10	$31.42	$31.425	$50.68
Inert Gas Atmosphere	100066	$0.01	$0.065	$0.10
	Total =>		$31.49	$50.79

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Energy To Heat Insulation (Whr)	248221	$0.00005	$0.0008	$0.001
To Evaporate Remaining Binder (Whr)	57283986	$0.00005	$0.1940	$0.313
To Heat Batch (Whr)	2323479	$0.00005	$0.0079	$0.013
To Heat Batch Support (Whr)	1161740	$0.00005	$0.0039	$0.006
Soaking Heat (Whr)	11189768	$0.00005	$0.0379	$0.061
Total Using Assumed Firing Efficiency		=>	$0.611	$0.986

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.001	$13.50	$0.01	$0.02
Capital Charges		12.0%	$7.85	$12.67
Taxes		1.2%	$0.49	$0.78
Insurance		1.0%	$0.00	$0.00
Maintenance		30.0%	$13.31	$21.47
		Total =>	$21.66	$34.94

		$/piece	$/lb
==========>COST OF FIRING	=>	$0.00	$0.00
==========>COST AFTER FIRING	=>	$31.42	$50.68

COST DISTRIBUTION

Materials	$17.53	56
Energy	$0.15	0
Labor	$1.87	6
Capital Charges	$8.30	26
Other	$3.57	11

MACHINE SHOP

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
CNC Lathes	134	$50,000	6.70E+06
Special Chucks	134	$5,000	6.70E+05
Tooling Crane	50	$15,000	7.50E+05
Benches and Cabinet	134	$500	$67,000
Miscellaneous Tools	50	$10,000	5.00E+05
Total ($/plant) =>			8.69E+06

====> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Fired Part	1.04	$35.70	$35.70	$57.58
Coolant	0.01	$0.20	$0.00	$0.00
Grinding Wheels	0.04	$7.00	$0.30	$0.49
Total =>			$36.01	$58.08

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	0.776	$0.0525	$0.041	$0.066
		Total =>	$0.041	$0.066

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.104	$13.50	$1.41	$2.27
Capital Charges		12.0%	$0.80	$1.29
Taxes		1.2%	$0.05	$0.08
Insurance		1.0%	$0.00	$0.00
Maintenance		6.0%	$0.27	$0.44
		Total =>	$2.53	$0.00

		$/piece	$/lb
==========>COST OF MACHINING	=>	$2.88	$4.64
==========>COST AFTER MACHINING	=>	$38.58	$62.22

COST DISTRIBUTION

Materials	$17.90	46
Energy	$0.60	2
Labor	$3.28	9
Capital Charges	$11.09	29
Other	$5.70	15

QUALITY CONTROL AND STORAGE

==========> EQUIPMENT	UNITS	$/UNIT	$/plant
Ultrasonic Testers	8	$25,000	$200,000
Special Tables, Jigs, and Other Miscellaneous Equipment	2	$58,000	$116,000
Storage Racks(30discs/rack)	10	$1,000	$10,000
	Total ($/plant) =>		$326,000

==========> PROCESS MATERIALS	UNITS	$/UNIT	$/piece	$/lb
Machined Parts	1.02	$38.58	$38.58	$62.22
	Total =>		$38.58	$62.22

==========> ENERGY	UNITS	$/UNIT	$/piece	$/lb
Electricity (kwh)	0.032	$0.0525	$0.002	$0.003
		Total =>	$0.002	$0.003

==========> OTHERS			$/piece	$/lb
Direct Labor (man-hours)	0.017	$13.50	$0.23	$0.37
Capital Charges		12.0%	$0.03	$0.05
Taxes		1.2%	$0.00	$0.00
Insurance		1.0%	$0.00	$0.00
Maintenance		6.0%	$0.01	$0.02
		Total =>	$0.27	$0.44

		$/piece	$/lb
==========>COST OF QUALITY CONTROL	=>	$0.27	$0.44
==========>COST AFTER QUALITY CONTROL	=>	$38.85	$63.94

COST DISTRIBUTION

Materials	$17.90	46
Energy	$0.60	2
Labor	$3.51	9
Capital Charges	$11.12	29
Other	$5.72	15

TOTALS

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

	$/lb	percent
Material Preparation	$27.35	40.37%
Injection Molding	$15.73	23.21%
Green Machining	$0.00	0.00%
Binder Removal	$12.70	18.75%
Firing	$6.90	10.18%
Finishing	$4.64	6.85%
Inspection	$0.44	0.65%
Total ($/plant) =>	$67.76	100.00%

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

	$/piece	$/lb	Percent
Materials	$17.90	$28.86	46.1
Energy	$0.60	$0.97	1.6
Labor	$3.51	$5.67	9.0
Capital Charges	$11.12	$17.94	28.6
Other	$5.72	$9.22	14.7
Total ========>	$38.85	$62.66	

$/kg ====> $137.85

========> ASSUMPTIONS

POWDER COST ($/lb)	$20.00
PERCENT BINDER	38%
PLANT CAPACITY (pc/yr)	2.00E+06
BINDER BURNOUT TIME (hr)	72
FIRING TEMPERATURE (F)	3092
TOTAL YIELD	83%

INTERNAL DISTRIBUTION

1. R. B. Braid
2. B. L. Bush
3. J. B. Cannon
4-9. T. R. Curlee
10-15. S. Das
16. P. S. Gillis
17. D. L. Greene
18. E. L. Hillsman
19. P. J. Hughes
20-25. D. R. Johnson
26. C. R. Kerley
27. J. O. Kolb
28. M. A. Kulisha
29. R. Lee
30. C. G. Rizy
31. D. E. Reichle
32. R. B. Shelton
33-38. S. G. Wilson
39. P. D. Witcher
40. ORNL Patent Office
41. Central Research Library
42. Document Reference Section
43-45. Laboratory Records
46. Laboratory Records - Record Copy

EXTERNAL DISTRIBUTION

47. Assistant Secretary for Conservation and Renewable Energy, Office of Transportation Technologies, U.S. Department of Energy, Washington, D.C.

48. B. Buchanan, Computer Science Department, University of Pittsburgh, 206 Mineral Industries Building, Pittsburgh, PA 15260.

49. A. Hirsch, Vice President, Environmental Sciences, Director, Washington Operations, Midwest Research Institute, 5109 Leesburg Pike, Suite 414, Falls Church, Virginia 22041.

50. H. M. Ingram, Director, Udall Center for Studies in Public Policy, The University of Arizona, 803/811 East First Street, Tucson, Arizona 85719.

51. C. D. MacCracken, President, Calmac Manufacturing Corporation, 101 West Sheffield Avenue, P.O. Box 710, Englewood, New Jersey 07631.

52. J. B. Shrago, Director, Office of Technology Transfer, 405 Kirkland Hall, Vanderbilt University, Nashville, Tennessee 37240.

53. M. Williams, Professor, Department of Economics, Northern Illinois University, DeKalb, IL 60115.

54. Office of Deputy Assistant Manager for Energy Research and Development, DOE-ORO, P.O. Box 2008, Oak Ridge, TN 37831-6269.

55-64. OSTI, U.S. Department of Energy, P.O. Box 62, Oak Ridge, TN 37831.

END

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4/8/92