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# Ceramic Turbocharger Cost Modeling and Demand Analysis

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## SUMMARY

*Turbocharger rotors represent one of the most likely early uses for engineering ceramics. The use of ceramics in turbocharger rotors is currently limited by technical, institutional, and economic barriers. Cost simulations illustrate that if technical barriers are overcome, in a full-scale production facility ceramic rotors could be produced at a cost level competitive with metallic rotors. Based on a survey of the preferences of turbocharger manufacturers in terms of the value they place on cost, weight and performance, the future ceramic turbocharger market is projected to grow to over $40 million/year by the year 2000. This implies a silicon nitride powder demand of approximately 350 t by the year 2000.*

## 1 INTRODUCTION

Conventional automotive engines have undergone a rapid evolution since 1973, mostly driven by advances in fuel economy and pollution control devices. Despite the trends toward greater fuel efficiency and smaller engine sizes in automobiles (Table 1)[1] consumers in general, and particularly those in the US, have been unwilling to give up engine performance. Automotive manufacturers have turned to turbocharging as a method of power boosting a conventional engine. The turbocharger system itself can be a bolt-on unit requiring little or no redesign, and is considered a sporty or luxury item, which carries a price premium.

Currently, turbocharger rotors are manufactured from high-chromium

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**TABLE 1**
Number of Vehicles with 4, 6 and 8 Cylinders Engines in the USA

| *Model year* | *4-Cyl* | *6-Cyl* | *8-Cyl* |
|---|---|---|---|
| 1970 | 2 300 | 974 000 | 6 610 000 |
| 1971 | 520 000 | 880 000 | 5 781 000 |
| 1972 | 851 800 | 970 100 | 7 201 000 |
| 1973 | 887 900 | 1 023 700 | 8 398 700 |
| 1974 | 1 058 800 | 1 558 800 | 5 719 100 |
| 1975 | 565 443 | 1 254 158 | 4 828 081 |
| 1976 | 869 266 | 1 762 965 | 5 813 129 |
| 1977 | 599 724 | 1 708 767 | 7 215 572 |
| 1978 | 939 611 | 2 211 509 | 6 102 612 |
| 1979 | 1 664 756 | 2 262 087 | 5 641 420 |
| 1980 | 2 308 556 | 2 682 626 | 2 358 547 |
| 1981 | 2 827 622 | 2 358 025 | 1 909 211 |
| 1982 | 2 362 081 | 1 733 692 | 1 614 348 |
| 1983 | 2 382 274 | 1 793 980 | 1 982 252 |

steels and superalloys (primarily Inconel 713C and Inconel 738). However, ceramics have a lower inertial mass, which increases the operating efficiency, and are potentially less expensive in terms of overall production cost. Currently, silicon nitride is the preferred ceramic material for turbocharger rotors. Ceramic rotors are, at present, significantly more expensive than current metallic rotors. Present vendor quotations for ceramic rotors are 150–200% higher than the current price for a metallic rotor. This is partly because they are not being fabricated in production scale quantities. Costs could therefore drop dramatically if production increases.

The perceived benefits of using ceramics in turbocharger rotors, relative to the conventional metal alloy Inconel 713C, include:

(a) Weight reduction: ceramic exhaust rotors are approximately one third of the weight of a metal rotor. Consequently, they improve transient response. Future use of ceramic rotors would allow a redesign of the rotor housing, resulting in a smaller, lighter unit.
(b) Strength at high temperatures: ceramic rotors maintain their strength at significantly higher operating temperatures than metal rotors, thereby providing greater fuel economy. The higher operating temperatures available with ceramics will lead to reduced diesel engine emissions.
(c) Cost reduction: ceramic rotors could potentially cost less than current metallic rotors.

Tests have demonstrated improved engine performance with ceramic turbocharger rotors,[2-4] but other factors still limit their widespread use. For example, future rotor housing designs, which could result in both cost and weight savings, will not occur until ceramics use becomes widespread. The reliability and durability of ceramic rotors remain low; damage from foreign objects is a particular concern which will slow the penetration of ceramics into the turbocharger market. Damage by foreign objects can be reduced by using different materials upstream of the rotor.

Since ceramics will compete in the automotive market largely by price, a cost model was developed to estimate the production cost for ceramic rotors made by injection molding. Firing options in the model include either a continuous sintering process or sintering with a final hot isostatic pressing (hipping) step (to enhance various ceramic properties). The model includes technical as well as economic factors. For example, since injection-molded rotors currently contain up to 40% plastic binders and waxes,[5,6] binder removal cycle times are extremely long,[7-9] increasing production costs. Other costs include injection-molding tools, which are complex and expensive ($40 000–60 000/tool).

The production cost model is used to estimate the cost of manufacturing turbocharger rotors based on specific assumptions about the process technology. Cost analyses were combined with current turbocharger market projections and an assessment of the performance characteristics desired for turbocharger rotors. Cost estimates for future ceramic rotor production were compared to present costs of metallic rotors and combined with the performance requirements for turbocharger rotors. From these data an estimate of the percent and rate of ceramics penetration into the turbocharger market was made.

## 2 TURBOCHARGER ROTOR COST ANALYSIS

Production costs for an injection-molded silicon nitride turbocharger rotor were estimated.[10] The rotor selected for the analysis has a final weight of approximately 60 g. This size is suitable for automotive applications, and is equivalent to a silicon nitride rotor with a density of $3{\cdot}2\,\mathrm{Mg/m^3}$ which could be used in a Garrett T-2 turbocharger assembly.

The production cost model generates results based on a series of input assumptions. Table 2 lists the costs and cost distributions for an injection-molded turbocharger rotor; it also lists some of the assumptions on which these costs are based.

In Table 2 the total yield assumption of 86% is extremely high. To achieve such a yield in a ceramic process with approximately nine process steps, a 99% yield would have to be achieved at each step. An 86% yield is therefore

TABLE 2
Cost Distributions, Factor Costs and Cost Model Assumptions for a Ceramic T-2 Turbocharger Rotor Formed by Injection Molding

*Cost distributions*

| *Manufacturing process step* | *Value added per step ($/rotor)* |
|---|---|
| Material Preparation | 3·51 |
| Injection Molding | 0·92 |
| Binder Removal | 0·25 |
| HIP/Sinter | 1·62 |
| Finishing | 1·41 |
| Inspection | 0·68 |
| Total | 8·41 |

*Factor costs*

| *Costs* | *Value added per step ($/rotor)* |
|---|---|
| Materials | 4·36 |
| Energy | 0·07 |
| Labor | 1·54 |
| Capital Charges | 1·76 |
| Other | 0·67 |
| Total | 8·41 |

*Cost model assumptions*

| | |
|---|---|
| Powder cost | $44/kg |
| Percent Binder | 38% |
| Production Volume | 250 000 pieces/year |
| Binder Burnout Time | 40 h |
| Firing (HIP) Temperature | 2 100°C |
| Total Yield | 86% |

unlikely given current production methods, the degree of automation, and the quality of the initial raw material. Consequently, the sensitivity of the process to yield variations was examined; results are presented in Figs 1 and 2.

Presently, yields for ceramic turbocharger rotors may be as low as 10% overall, making the total cost per rotor well above $50, assuming a volume of 250 000 rotors/year (Fig. 1). The sensitivity of cost to the yield at two process steps (injection molding and firing) is illustrated in Fig. 2. From these results

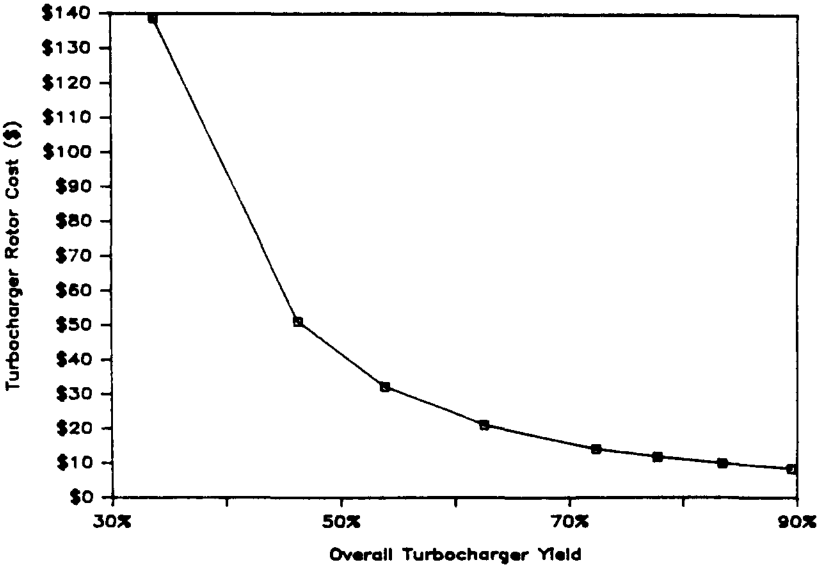

**Fig. 1.** Turbocharger rotor cost versus overall yield.

it is evident that improved processing is critical in the final processing stages because value is added to the material throughout the production sequence. Improvements in the materials themselves can also decrease the overall cost, by reducing rejection rates at each stage.

The sensitivity of the overall cost to the volume of ceramic rotors

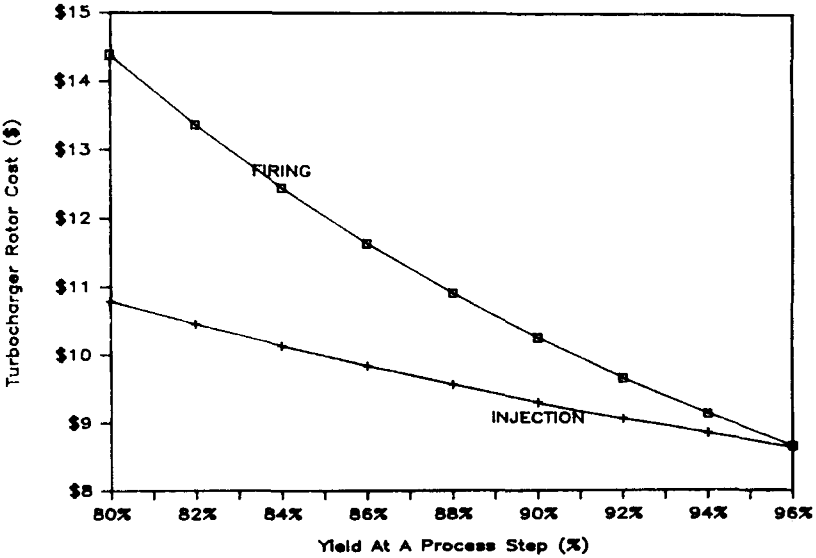

**Fig. 2.** Turbocharger rotor cost versus yield for two process steps.

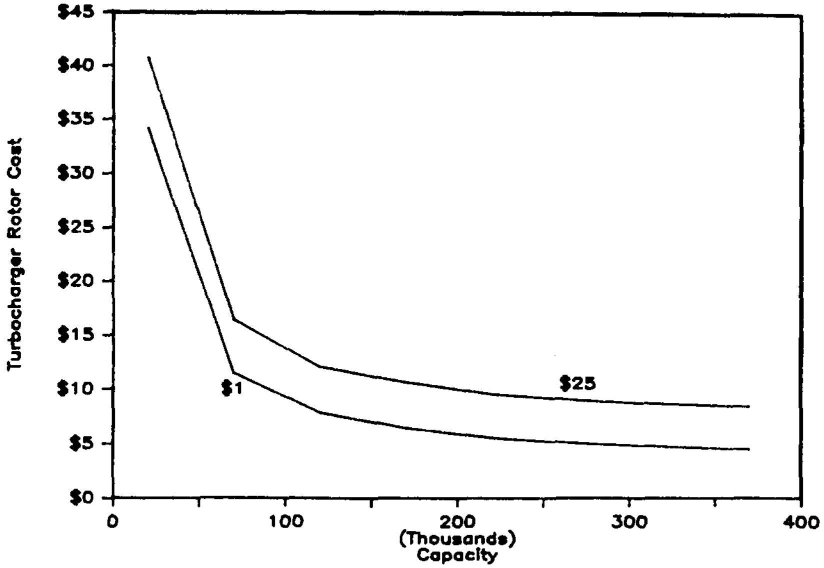

Fig. 3. Turbocharger rotor cost versus volume produced (capacity) for powder costs of $2·2 and $55/kg.

produced is shown in Fig. 3. Some of the key assumptions involved in the generation of this plot are: (1) powder cost; (2) tooling cost and life; and (3) overall yield as a function of volume of rotors produced. A maximum silicon nitride powder cost of $55/kg was assumed; a minimum cost of $2·2/kg. The area between the maximum and minimum powder costs on the graph represents the most probable range. It is unlikely that powder costs will ever be as low as $2·2/kg, and $55/kg is artificially high. The tooling cost and tool life also greatly affect the cost of producing ceramic rotors by injection molding. Initial investments can be as high as $40 000–65 000/die. However, these are prototype tools: a $40 000 die was assumed in this analysis to have an average life of 50 000 rotors.

Yield variations were also analyzed to investigate cost as a function of production volume. The following yield relationships were used to relate overall yield to production volumes of ceramic rotors:[10]

If volume < 10 000, yield = 46%
If volume 10 000–50 000, then yield = 54% (1)
If volume 50 000–100 000, then yield = 72%
If volume 100 000–200 000, then yield = 83%
If volume > 200 000, yield = 89%

The relationship represents an estimated learning curve assumption, or an assumption that as production volumes increase, the manufacturing process generally becomes more efficient. The above yield variations with volume

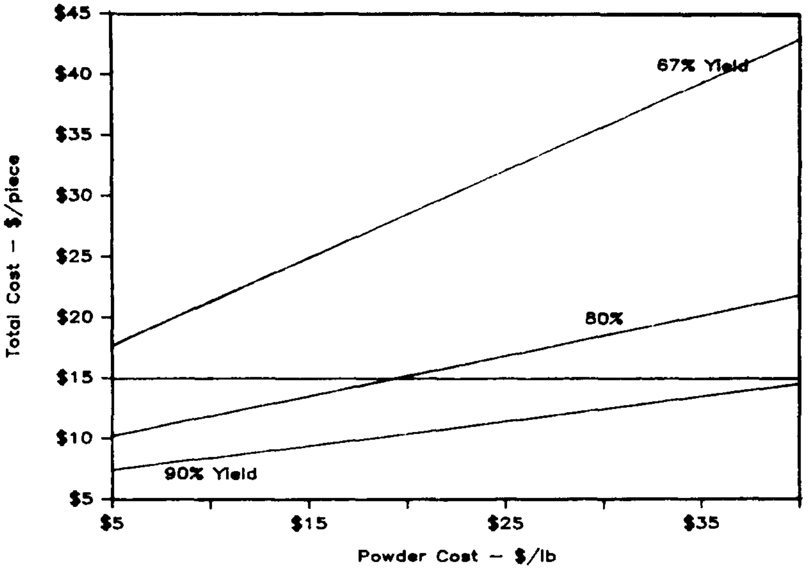

**Fig. 4.** Turbocharger rotor cost versus powder cost at different overall yields (1 lb = 0·454 kg).

have been taken into account and strongly influence the curve shown in Fig. 3. The overall yield increases from 46% with pilot plant scale production of 10 000 rotors/year to as high as 89% overall with a commercial scale operation of over 200 000 rotors/year. Ceramic rotor costs become competitive above 70% overall yield, which in this scenario represents a production volume of 100 000 rotors/year.

Figure 4 illustrates graphically how different initial powder costs and process yields influence the total cost of an automotive ceramic turbocharger rotor. The target price for such a ceramic rotor is between $12 and $15. The production process is based on the same assumptions listed in Table 1 for the injection-molded rotor. Although prototype production yields for ceramic turbocharger rotors may be lower than 25%, if the learning curve assumption holds, future yield improvements could make the cost of the ceramic rotor competitive with the current metallic rotor.

## 3 AUTOMOTIVE TURBOCHARGER DEMAND ANALYSIS

Some projections indicate a potential turbocharger market size of $200 million by 1990.[11] At the present level of ceramics technology, ceramic rotors cannot be manufactured with the required reliability at a reasonable cost, nor is there presently an adequate method of joining the ceramic to the metal shaft. The potential for ceramics use in passenger cars (both standard and sport cars) will be examined here. The material requirements for ceramic rotors in truck diesel turbochargers will not be included due to the higher reliability and long-term durability required.

A survey was used to quantify the views of experts in the area on performance requirements for turbochargers. Current market projections for turbocharged automobiles were examined to estimate the potential for ceramics in turbocharger rotors based on cost, properties, and performance attributes. The market assessment results were combined with the cost estimates of the previous section to determine the potential size and value of the ceramic rotor market and estimate the time to commercialization.

The survey mentioned above addressed three characteristics of turbocharger materials: (1) rotor cost, measured in dollars; (2) rotor weight, measured in kilograms; and (3) rotor performance, measured by an index. The performance index was a subjective measure of the overall behavior of the rotor system, rating such factors as operating temperature, transient response, and lifetime. The index was measured from 1 to 10, with 1 representing the worst possible performance and 10 the best. The performance index was defined by the interviewees as the performance of the final turbocharger unit in operation, regardless of the material used in the rotor. Other characteristics which turbocharger users and manufacturers feel are important are durability and reliability. Interviewees included rotor manufacturers, turbocharger systems manufacturers and engine manufacturers from the US and Japan.

The market for turbochargers varies among the major geographic sectors (the USA, Europe and Japan). Attitudes towards using ceramics in turbochargers also vary with location. For example, existing rotor performance, or the effect of the rotor on overall performance of the turbocharged system, varied widely with survey respondent. US manufacturers felt that the present performance of their turbocharged systems ranked at least 8 on a scale of 1 to 10. On the other hand, Japanese manufacturers rated their current performance at 4 to 5. This difference in attitude strongly affects the turbocharger supplier's attitudes towards the use of new materials. If the manufacturer feels his product performs close to the maximum achievable performance level he will be reluctant to change any part of the overall system. If, however, the manufacturer feels that significant improvements can be made to his product's performance he will be more willing to risk changing his present system.

The views of four manufacturers on cost/weight tradeoffs are illustrated in Fig. 5. Survey results indicated that current metallic rotor costs are in the \$7–10 range and the current weight of the rotor itself is approximately 0·2 kg. The curve illustrates that weight reductions can demand a price

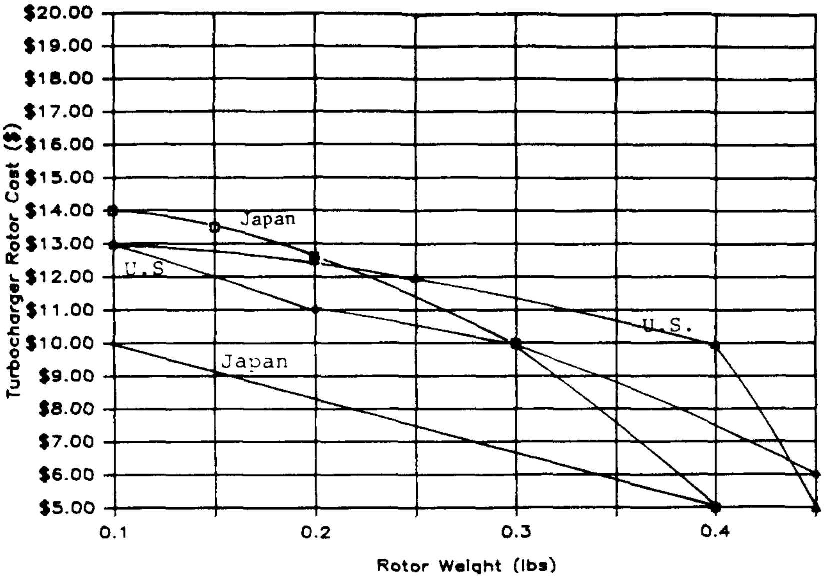

**Fig. 5.** Turbocharger rotor cost/weight tradeoffs for two US and two Japanese manufacturers (1 lb = 0·454 kg).

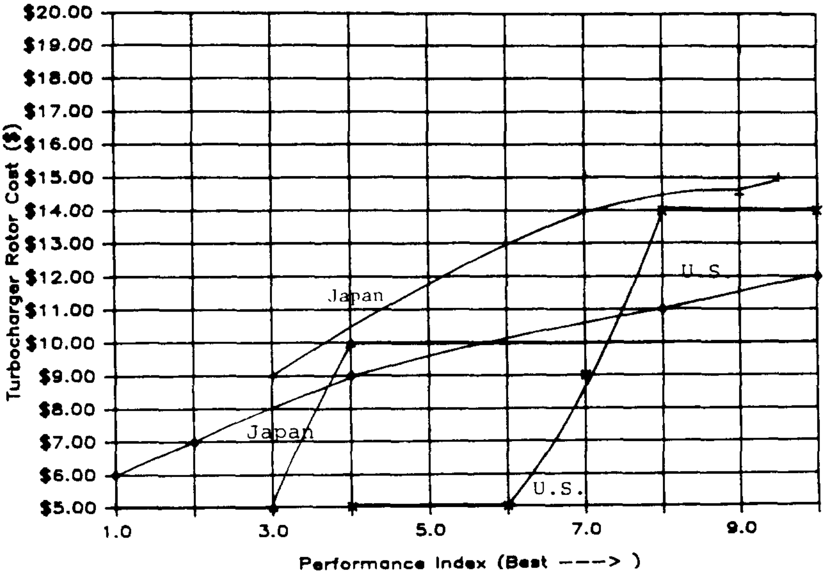

**Fig. 6.** Turbocharger rotor cost/performance tradeoffs for two US and two Japanese manufacturers (1 lb = 0·454 kg).

premium. The weight reduction from 180 g to 45 g can demand a price premium from 40% to over 100%. The manufacturers surveyed were willing to pay a maximum of $14 for a weight reduction of 140 g, assuming the performance of the rotor was constant save for the increased performance due to weight reduction.

Cost/performance tradeoffs (Fig. 6) varied more among the individuals surveyed than did the cost/weight tradeoffs. This is not surprising considering the differences in attitudes between US and Japanese manufacturers towards current performance levels. The analysis indicated that if ceramic rotors are to achieve commercial success they must perform as well as the current metallic rotor at the same cost. Japanese manufacturers felt that a ceramic rotor would have to cost the same or be cheaper than a metallic rotor, regardless of performance, because it is a new material substituting in an existing application.

The performance of a turbocharger is dependent on the type of driving required, which differs between the USA, Europe and Japan. US cars are turbocharged for performance, particularly in the Chrysler line which produces very few V-6 engines. To date, General Motors and Ford Motor Company have produced less turbocharged vehicles than Chrysler (Table 3).[12] Of all turbocharged vehicles, only those with higher prices will be able to absorb the cost of a ceramic rotor in the near future. However, should the technology improve, a more widespread use could be viable because at a lower cost ceramic rotors could be used in a wider range of vehicles.

Turbocharging is more prevalent in European cars, which have traditionally been characterized by smaller displacement engines, lower horsepower and high performance. The added turbo-boost helps performance with a minimal decrease in fuel efficiency. Although turbocharging is prevalent, the adoption of ceramic rotors by European manufacturers may be slow due to the already high costs of these automobiles and the poor financial status of parts of the European auto industry (e.g. Renault). If, however, the use of ceramics becomes widespread in the USA, the European market would follow to compete in the international automotive market.

**TABLE 3**
The Number of Turbocharged Vehicles Produced by US Manufacturers in 1984

| *Manufacturer* | *Number turbocharged* |
|---|---|
| General Motors Corp. | 20 872 |
| Ford Motor Co. | 33 084 |
| Chrysler Corp. | 104 369 |

Porsche already has an aluminium titanate lining on its 944 Turbo exhaust port, demonstrating the company's desire to take advantage of the added insulating benefits of that ceramic material.

The Japanese market is very different from either the US or European markets. Japan is making an effort to use ceramics widely in their automobiles. Efforts have been made to incorporate several small ceramic engine components such as prechambers and glow plugs. The major suppliers of ceramic rotors in the USA are Japanese companies: Kyocera International and NGK Spark Plug and Insulators. Companies that manufacture turbochargers in Japan (i.e. MHI and IHI) are also involved in the development of ceramic rotors (Garrett Corporation in the USA is also researching ceramic rotors). Therefore if ceramics are technically viable for this application, and the low-cost scenarios previously described develop, the Japanese market will be the first to employ ceramic rotors on a large scale.

The automotive diesel engine, which comprises 2% of the total automotive engine market, requires power boosting for adequate performance. Turbocharging, turbocompounding and supercharging are all methods of increasing diesel engine performance. Furthermore, due to its lighter weight, the ceramic rotor could reduce engine lag, an important problem for diesel engines. There is also a large profit margin on turbocharger components: consumer perceptions of this luxury feature on diesel engines allow a $1000 increase in the price of the automobile while the actual cost of a turbocharger unit is only $250–400.[13] Rotor costs are less than 10% of the overall cost of the turbocharger unit, so some flexibility on the cost of the rotor could be tolerated for increased performance.

## 4 PROJECTING CERAMICS USE IN THE TURBOCHARGER MARKET

The cost scenarios described earlier indicate that at some future date, with specific assumptions about production volumes, operation yields, raw material costs, and process parameters, ceramics could compete on a cost basis with existing metal rotors. Before this happens, however, ceramic rotors could demand a price premium of up to 40% because of the expected performance levels described previously. Projections of the introduction of ceramics into the turbocharger market are described below.

Although some turbocharger manufacturers have announced plans to use ceramic rotors, it is unlikely that rotors will be manufactured in quantities larger than a few thousand until at least the 1989 model year. Currently there is limited production capacity since large-scale production facilities are nonexistent, and it is unclear how long it will take to scale up existing processes. Initially the market for ceramics will be small, growing to within the range of 10 000 rotors in the first two years if durability is demonstrated and the supply of ceramic powders and rotors is assured.

At such a low level of production, a rotor price of $20/rotor was assumed for the analysis. Currently this price is twice that for a metal rotor. The rotor itself, however, is only about 10% of the overall cost of the turbocharger system. Therefore, for high-performance cars a price premium for enhanced overall turbocharger performance could be demanded for the rotor. As volumes increase, the rotor price is expected to decrease to $12/rotor or below. Figure 7 illustrates the potential penetration of ceramic rotors into the turbocharger market. The projection of the number of turbocharged cars was adapted from a model developed at Argonne National Laboratory.[14] Ceramic rotors are assumed to reach a maximum of 50% penetration into the turbocharger market because they are most desirable only in higher-priced, luxury/high-performance vehicles.

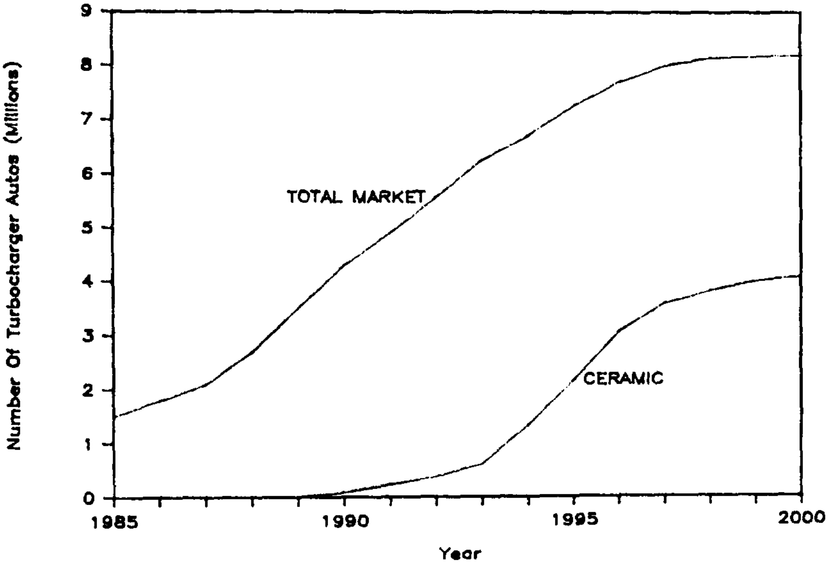

Fig. 7. Projected ceramics penetration into the turbocharger market.

The projected number of ceramic turbocharged vehicles was used to predict the overall dollar value of the future ceramic rotor market. The cost of producing this volume of rotors was also estimated. Based on the yield assumptions made in Fig. 2 (derived from the set of yield relationships (eqn (1)) described earlier), Fig. 8 compares the overall production cost with the expected market value. In this graph, the curves appear to cross around 1989

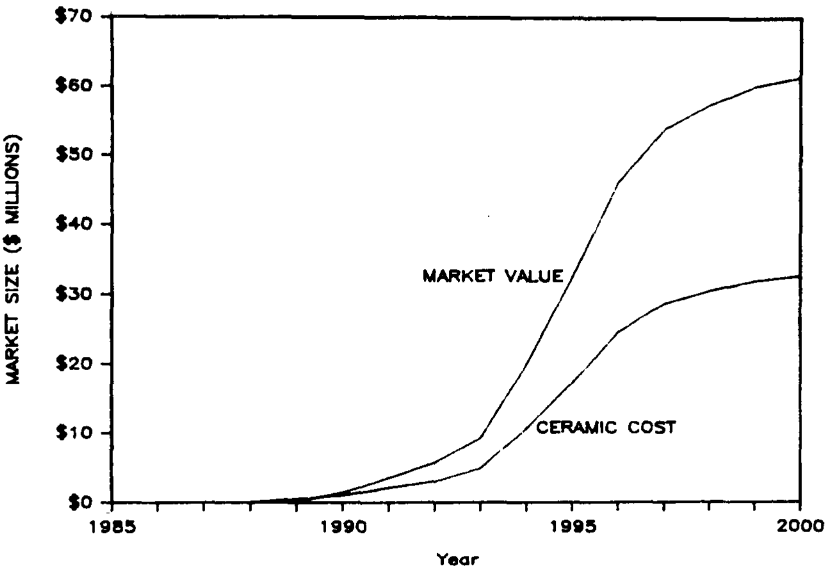

Fig. 8. Projected ceramics production cost and market value for turbocharger rotors.

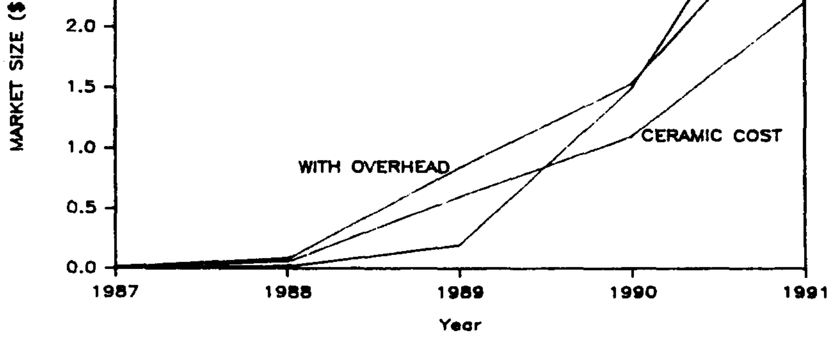

Fig. 9. Projected crossover point of production cost and market value for ceramic turbocharger rotors.

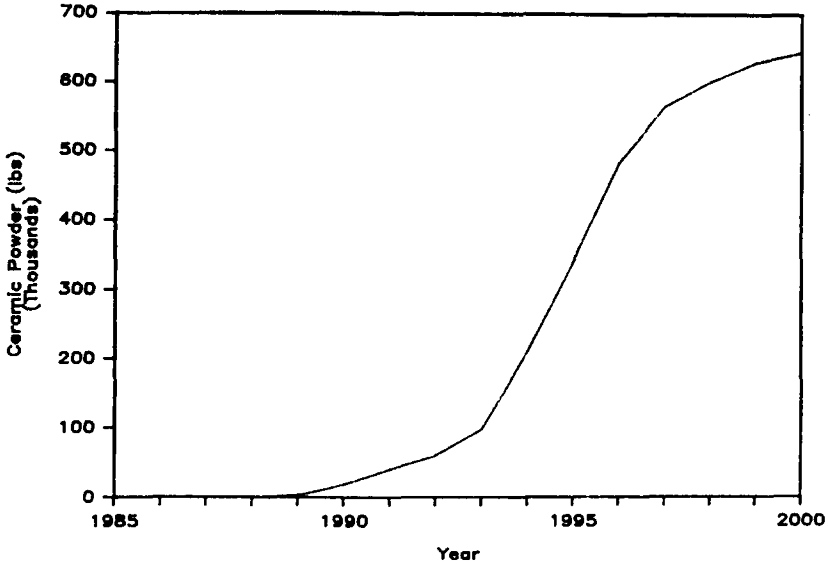

**Fig. 10.** Projected silicon nitride powder requirements for turbocharger rotors (1 lb = 0·454 kg).

to 1990. An enlargement of this region is illustrated in Fig. 9. Since the cost curve is an estimate of production costs including only direct overhead, 40% overhead was added to the cost as an estimate of the total cost to the producer. This cost was compared to the estimates of market value and, based on the stated assumptions, production volumes of 100 000 rotors/year, with a total yield in the 70% range and a rotor selling price of $14/rotor are required for profitable manufacturing.

The future availability of ceramic material for turbocharger applications is predicated upon adequate supplies of ceramic powders. Currently, production capacity of silicon nitride is approximately 25 000 kg/year. Figure 10 is a projection of the silicon nitride powder requirements for turbocharger rotors; the yield assumptions, described earlier, are included. The requirement for advanced powders is at least an order of magnitude higher than current production, and this only accounts for one application. If advanced ceramic applications are to become widespread, powder production must increase.

## 5 CONCLUSIONS

An assessment of the engineering requirements for turbocharger rotors indicates that ceramic materials, with improved durability, could be the material choice for this application. However, reliability and durability of silicon nitride rotors must be demonstrated to the satisfaction of the turbocharger manufacturer before these materials will gain widespread use. If this can be achieved, ceramics use could expand to 50% of the growing automotive turbocharger market.

The cost scenario indicates that ceramics, under a specified set of assumptions, could be cost-competitive with the nickel-based (Inconel) alloys currently used. However to be competitive, automated, full-scale production facilities are required and yields must increase to at least 70%. As the volume of rotors produced increases, powder prices are expected to fall. Materials suppliers, however, must also expand and automate their powder production facilities, or the volume of materials required for this and other advanced ceramic applications will not be available.

The dilemma facing expanded use of ceramic turbocharger systems is that manufacturers will not use ceramic rotors on a widespread scale, or invest in redesigning the system, until they can be assured of a reproducible, reliable rotor at a reasonable cost. Ceramic rotor suppliers do not have an incentive to scale up production facilities without a guaranteed market. Moreover, until commercial-scale production facilities are in operation, the exact properties and costs of ceramic rotors will be uncertain. Finally, the quantity and quality of powder supplies are currently limited. A clear demonstration of the performance of silicon nitride (or other ceramics) in turbocharger applications will be required to provide momentum to the commercialization process.

## ACKNOWLEDGEMENT

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