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# Structural Ceramics in Transportation: Fuel Implications and Economic Effects

ARVIND P. S. TEOTIA and LARRY R. JOHNSON

ABSTRACT

A description based on a study at Argonne National Laboratory funded by the U.S. Department of Energy is given of the potential application of structural ceramics in motor vehicle engines. With their high-temperature strength and their resistance to wear and corrosion, these high-technology ceramics are excellent candidates for the harsh environment of the advanced engines being considered for automobiles and trucks. The critical role of ceramics in the adiabatic diesel, gas turbine, and Stirling engines is discussed, along with an indication of the fuel efficiency potential and multifuel capability of each engine. A market penetration analysis of the advanced engines uses two alternative commercialization scenarios for ceramic component engines--one with the United States dominating the market and the other with Japan dominating. Changes in major national economic indicators are noted after simulations of the economy with a macroeconomic model. Effects on the use of strategic materials are also noted.

Research in energy conservation technologies was stimulated by the energy crises of the 1970s. The crisis situation no longer exists, but the interest in improving energy efficiency remains. The transportation sector has historically been vulnerable to energy disruptions and price shocks and remains susceptible to them in the long-term future despite the current petroleum glut. Indeed, as the residential, commercial, and industrial sectors have increased their use of nonpetroleum fuels, the transportation sector has consequently begun to account for a significantly larger share of petroleum use. From the 1950s through the 1970s--even after the first oil crisis--transportation's share of oil use consistently remained between 53 and 55 percent. This share has steadily increased since 1979, and transportation is now responsible for more than 61 percent of the petroleum used in the United States (1).

In the mid-1980s, highway transport continues to dominate transportation energy use, with automobiles and trucks consuming nearly three-fourths of the sector's total energy use (2). As a result, considerable research is being performed on power systems that can potentially provide fuel efficiencies beyond the limits of current gasoline and diesel engines or that can burn nonpetroleum fuels. Much of this research has concentrated on batteries for electric vehicles or on advanced engines such as the gas turbine, Stirling, and adiabatic diesel. The principal limitation of heat-engine technologies has been mechanical strength at high temperatures. If reliable structural ceramics can be produced for vehicle engines, an opportunity will arise for the marketing of new fuel-efficient vehicles that use the advanced engine designs. The potential fuel savings that may result from commercialization of new engine technologies, the associated macroeconomic benefits [e.g., changes in gross national product (GNP), employment, balance-of-trade], and the implications for ceramics in reducing U.S. dependence on strategic materials are described.

## FUEL-SAVING POTENTIAL OF CERAMICS IN MOTOR VEHICLE ENGINES

### Characteristics of Ceramics

Ceramics are made from common, readily available materials such as carbon, silicon, oxygen, and nitrogen. Consolidation of compounds at high temperatures, sometimes under pressure, is used to form a variety of products from pottery to electronic components. Conventional ceramic products are widely used in many household and industrial applications.

Advanced ceramics, also called engineered ceramics, high-performance ceramics, or--in Japan--fine ceramics (because of the extremely small particle size of the ceramic powders), are relatively new. These materials have been developed for use in electronic components (capacitors, resistors, and semiconductors), cutting tools, bearings, and engine parts. Advanced ceramics differ from conventional ceramics in that the raw materials for the advanced ceramics are based on more sophisticated compounds, such as aluminas, carbides, nitrides, borides, and zirconia, that enhance the desired properties of the ceramics. Engine applications are just beginning to be developed but, of all the possible uses, they have the most potential for growth and ultimate profitability (3).

Structural ceramics (as the term implies, there is a load-bearing requirement for the finished product) have a number of physical and mechanical properties that enhance their use in a variety of industries. Of particular importance in motor vehicle engines is the bonding of ceramics to form a crystalline structure that results in high-temperature mechanical strength plus wear and corrosion resistance. The well-known negative quality of ceramics--extreme brittleness--remains a problem. Substantial research is being directed toward improving ceramic microstructure to overcome its brittleness and toward improving quality control during production.

### Ceramics Applications in Vehicle Engines

Government and industry have identified, and conducted research on, a number of alternative heat engines for automobiles and trucks. The most promising are the gas turbine, the adiabatic diesel (both internal combustion engines), and the Stirling (an external combustion engine). The thermal efficiencies of these engines are greatly enhanced by increasing their operating temperatures. To achieve fuel efficiencies that would make these engines competitive with existing gasoline and diesel engines, new materials must be developed to operate at higher temperatures. The most likely candidate materials are superalloys, carbon composites, and structural ceramics. Only ceramics offer the potential low cost to make these engines economically and technically competitive (4). The potential fuel efficiencies and alternative fuel capabilities for each of these engines are described briefly. Select engine components that are candidates for manufacture from ceramic materials are also discussed.

### Components for Current Engines

The initial introduction of structural ceramics into heat engines will most likely be in the form of components or parts in existing gasoline or diesel engines. Through the replacement of metal components with ceramics, heat loss can be reduced, wear resistance improved, and weight lowered. The most immediate applications are likely to be in pushrods, tappets, seals, piston heads, cylinder liners, and turbocharger rotors (5). These applications will be more immediate than those in advanced engine designs because the parts are smaller (and are thereby subject to less stress) and consequently easier to produce in terms of controlling critical microstructural flaws. Depending on how extensively ceramics are used in conventional engines, fuel efficiencies should improve by 5 to 15 percent or more.

Of particular interest for the more immediate applications is the use of ceramics for turbocharger rotors instead of the traditional nickel alloys. Rotor weight will be reduced by two-thirds, which will in turn reduce inertia and improve rotor response. Use of a ceramic rotor may also eliminate the need for metal center bearings, the components most likely to fail in current turbocharger designs. The metal bearings can be replaced by ones of ceramic or by a system in which the lightweight ceramic shaft rides on a layer of air. The use of ceramics in turbochargers will eventually allow the entire assembly to be redesigned, eliminating the need for the heavy containment structure that the metal rotor now requires. The total costs of turbochargers should also decline, resulting in wider use (6). As a result, smaller and more fuel-efficient engines can have the performance of larger engines.

### The Adiabatic Diesel Engine

An adiabatic process is one with no heat loss. Adiabatic engines accomplish this by eliminating the cooling system and insulating the combustion chamber to minimize the loss of heat. Thermal efficiency is improved by removing the cooling system, which also reduces the size and weight of the engine as well as its cost. Moreover, maintenance costs should be reduced and reliability increased, because 50 percent of heavy-vehicle engine failures are related to cooling systems (7).

A prototype adiabatic diesel engine in a 5-ton military truck has already been highway-tested. In a recent test, round-trip fuel economy between Washington, D.C., and Detroit exceeded 9 mpg, compared with a similar production engine in the same vehicle that averaged 6 mpg. Ceramic coatings were used throughout the combustion zone in the uncooled prototype.

Although adiabatic engine technology will most likely be introduced first in heavier truck applications, the concept applies to automotive vehicles as well. Preliminary assessments of an uncooled light-duty diesel indicate that a 15 percent fuel savings over conventional diesels should be easy to attain (8). Recent modeling efforts indicate that fuel savings could be much higher and that a multifuel capability is possible.

### The Gas Turbine Engine

The gas turbine already has a proven record in stationary power generation and in aircraft and marine applications. As an automotive power plant, the gas turbine offers the potential for improved fuel economy, multifuel capability, low maintenance requirements, and high reliability. Its major limitations currently appear to be poor efficiency under part-load conditions and slow acceleration. Higher operating temperatures will be required to improve efficiency, and ceramics are the most likely materials for such advanced designs.

Two separate industrial teams are conducting government-sponsored research on the advanced gas turbine for automotive use. The efficiency goal for a 3,000-lb automobile with a 100-hp gas turbine engine is 42 mpg with diesel fuel (compared with 31 mpg for an equivalent gasoline-powered vehicle or 37 mpg for a conventional diesel) (9).

The multifuel capability of the gas turbine is another major reason for continued interest in this technology. Tests with automotive gas turbines are usually conducted with gasoline, diesel fuel, and kerosene. Further tests are expected to demonstrate that the gas turbine can also use broad-cut petroleum fuels, alcohols, coal-derived fuels, and hydrogen (10).

### The Stirling Engine

A third alternative engine for vehicle applications is the Stirling. This external combustion engine uses a working gas, such as hydrogen or helium, that is alternatively heated and cooled to compress and expand it and provide the mechanical force. Although there are no commercial uses for the Stirling as yet, interest in it continues because it has the highest theoretical thermal efficiency of any practical heat engine. In addition, the Stirling offers the advantages of multifuel capability, improved fuel economy, low emissions, and low noise.

An 80-hp reference Stirling engine in a 3,000-lb vehicle is expected to achieve 46 mpg on diesel fuel. This fuel efficiency would require higher engine operating temperatures than are currently achievable. Again, ceramic components are likely to play an important part. From a fuels perspective, the Stirling is attractive because of its adaptability. The P-40 Stirling engine (developed by United Stirling of Sweden and installed in a 1977 Opel) has demonstrated the use of gasoline, kerosene, diesel fuel, and alcohols (10). In addition, shale oil-based diesel fuel and broad-cut aircraft fuel have been tested in the MOD 1 Stirling engine (an improved Stirling developed by Mechanical Technology, Inc., and tested in a 1979 AMC Spirit and a 1980 GM X-body) (9).

## MACROECONOMIC EFFECTS OF ADVANCED CERAMICS

### International Research Efforts

Major ceramic research programs focused on engine applications are under way in the United States, Japan, and West Germany. Most ceramic researchers in this country consider Japan to be the major U.S. competitor. Mueller, in 1982, noted two areas of concern for the United States (11). First, the United States trails Japan (and West Germany and Australia) in the development of new ceramic materials such as polycrystalline partially stabilized zirconia, a recent advanced ceramic with potential for use in heat engines. Second, a Japanese company has developed and successfully tested the first ceramic diesel engine. Ceramic components in this three-cylinder engine included pistons, wrist pins, cylinder sleeves, tappets, pushrods, and rocker arms.

A more recent survey of ceramic fabricators and engine manufacturers found a variety of opinions about which country was leading in advanced ceramics research, although there was general agreement that the Japanese have the momentum of government and industry cooperation. However, new materials programs in the United States may alter this perspective. Both Japan and the United States have areas of strength. The Japanese probably lead in zirconia-based ceramics and in developing long-range research programs that lead to early commercialization of products. The United States is considered the leader in basic research and has more experience in designing ceramic engine components and evaluating them on test rigs (5).

### Methodology for Estimating Economic Effects

A two-step approach was used to measure the economic effects of structural ceramics in a study at Argonne National Laboratory (ANL) funded by the U.S. Department of Energy (DOE). In the first step, a ceramic market penetration model was developed and used to estimate the market penetration of structural ceramic products. In the second step, the Data Resources, Inc., (DRI) annual macromodel of the U.S. economy was used to estimate macroeconomic effects in two alternative ceramic commercialization scenarios (12, 13). Highlights of these models are briefly described in the following paragraphs.

The general market penetration methodology is based on earlier ANL work that estimated the market penetration of new energy-efficient electric motors (14) and new cogeneration energy systems (15). The market penetration analysis was begun by selecting key structural ceramic applications, including bearings and other engine components, turbochargers, and gas turbines. The total market potential was obtained by estimating the 1981 sales of the conventional-material parts that could be replaced by ceramic parts. Most of the shipment value data for the conventional parts were obtained from the 1977 Census of Manufacturers (16). Sales were projected to the year 2005 using the growth rates of the industries from the DRI macroeconomic scenario TRENDLONG2007B (17).

Market penetration of various ceramic components in the year 2000 was subsequently obtained by multiplying the market potential by penetration rates estimated by industry. Several industry sources were asked to provide their expectations of the market potential of various ceramic applications. The results of this approach are expected to lead only to preliminary estimates of market penetration of structural ceramics components. A more thorough approach, such as that used in the previously mentioned ANL work (14,15), would have made use of the relative economics of ceramics and its competing technologies. However, for this analysis, the relative cost data were proprietary and consequently unavailable and cost data could not be developed in the time available.

The other model used in the ANL study was the DRI annual macromodel of the U.S. economy. This simultaneous-equation model contains 266 economic variables and simulates the major economic sectors, including consumption; business fixed investment;

residential fixed investment; trade; federal, state, and local governments; prices and wages; finance; and energy.

In the energy sector--of special interest in this study--this model is particularly strong. For example, total energy demand is estimated for electric utilities and the household, commercial, industrial, and transportation sectors. Energy supply is separated into domestic and imported sources.

## Scenarios for Commercialization of Structural Ceramics

Because it is unclear which country will achieve the technical breakthroughs first or how patent rights will be controlled, an accurate forecast cannot be made of the path that commercialization will take. It is clear that significant benefits will accrue to the companies that reach the marketplace first. They will receive direct benefits in terms of profits from the sale of ceramic components or from increased vehicle and engine sales due to the advantages of ceramic parts. However, there are also aggregate economic benefits that apply on a national level. Changes in GNP, employment, energy savings, and balance-of-trade accounts are some of the key quantifiable indicators of the influence of domestic or foreign dominance in a product area such as ceramics.

In this assessment, two separate scenarios were developed to provide a parametric analysis. The scenarios bracket the range of divergent views on commercialization of structural ceramics, focusing on the effects of either U.S. or Japanese dominance in the ceramic market in vehicle heat engines. This methodology is used not because either outcome is considered probable, but because of the magnitude of input variables that could be used to reflect each country's research funding, technical success, market strategy, and eventual market penetration. A base case scenario is provided for comparison; it assumes that there is no concerted government or industry effort to develop and commercialize structural ceramics in vehicle heat engines.

### U.S. Dominance

This optimistic scenario assumes considerable government and industry cooperation that effectively results in a national ceramics research and development program. Military applications are excluded from this analysis, but ceramic components (e.g., piston rings) are assumed to enter the market in heavy-truck engines by 1985. Ceramics in advanced engines such as the adiabatic diesel and the gas turbine are assumed to be introduced in the automotive and truck markets in 1990. The assumptions for market penetration are the upper limit of the potential vehicle market as reflected in discussions with industry contacts. For the United States to achieve dominance in structural ceramics one would also have to assume that there would be a reversal, or at least a slowdown, in the current pace of Japanese ceramic research. Such a change is conceivable, based on Japan's recent economic difficulties and budget constraints. The Japanese might view a strong U.S. research program in ceramics as building on the U.S. lead in the 1970s. As a result, the Japanese might decide to focus their research on other areas. In this scenario, U.S. success in the 1990s will cause the Japanese to renew their efforts so that by the end of the decade Japanese automobiles exported to the United States will have comparable technology.

### Japanese Dominance

This pessimistic alternative assumes that there will be no major national ceramic research in the United States, while Japan will continue with a substantial government and industry research effort. In this scenario, the U.S. ceramics industry considers the market too risky because of the strong Japanese research effort, although the potential for structural ceramics is recognized. The Japanese have traditionally focused on low-horsepower engines; consequently, they begin to introduce limited ceramic components in automobile engines in 1985. The Japanese share of total U.S. automobile sales naturally increases at the expense of domestic automobile manufacturers. The import market share in this scenario is limited to 30 percent. In view of the current voluntary import restraints, it is anticipated that at a 30 percent import share, trade restrictions, minimum-domestic-content laws, or licensing agreements would be imposed. The Japanese are not expected to enter the U.S. markets for heavy-duty trucks or stationary diesel and gas turbine engines without the alliance of a North American manufacturer.

## Comparative Economic Effects in Each Scenario

The largest sales potential and subsequent national economic effects in each of the scenarios can be expected in the automobile market because of its size (compared with that for heavy trucks or stationary engines). Because of the assumptions for market penetration in each scenario (automobile versus truck as the initial market, constrained market share, etc.), the ultimate macroeconomic effects are different from what might be anticipated if there was only an assumption of market penetration but with different countries leading.

Table 1 presents the new automobile sales in each scenario. In the U.S. dominance case, automobiles with ceramic engines gain a market share of 20 percent by the year 2000. This volume of domestic automobile sales would reduce import sales to 15 percent. In the Japanese dominance case, however, limiting foreign ceramic-engine automobile sales to 500,000 annually would keep the import share from exceeding 30 percent.

**TABLE 1 United States Automotive Market Penetration by Ceramic-Component Engines for the Alternative Scenarios**

| | Base Case | | U.S. Dominance | | Japanese Dominance | |
|---|---|---|---|---|---|---|
| Year | Total (x $10^6$) | Import (%) | Ceramic Engine[a] (x $10^3$) | Import (%) | Ceramic Engine[a] (x $10^3$) | Import (%) |
| 1985 | 10.9 | 23.4 | 0 | 23.4 | 10 | 23.4 |
| 1990 | 11.9 | 24.5 | 125 | 24.4 | 100 | 25.2 |
| 1995 | 12.6 | 24.2 | 1,270 | 19.0 | 500 | 27.8 |
| 2000 | 12.7 | 25.2 | 2,540 | 15.0 | 500 | 29.1 |
| 2005 | 13.0 | 25.9 | 3,580 | 15.0 | 500 | 30.0 |

[a]Automobiles powered by engines using structural ceramics.

For the sake of perspective, Figure 1 illustrates the relationships between the alternative scenarios and the historical share of imported automobiles. The U.S. dominance case would push imports back to their early-1970s (pre-energy crises) levels. The Japanese dominance case would cause imports to rise to a slightly higher level than that of the mid-1980s.

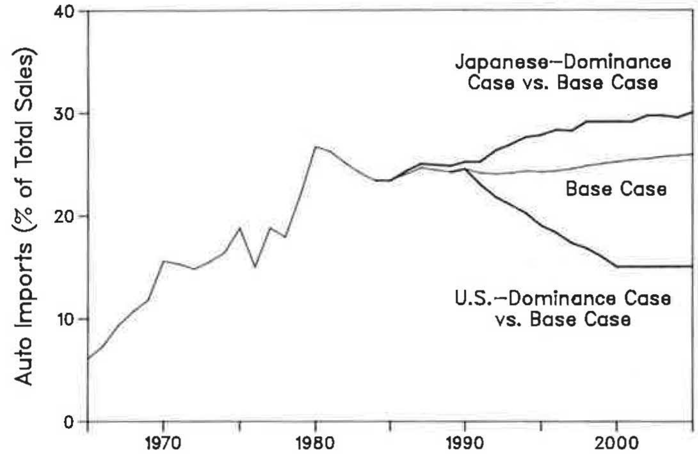


FIGURE 1 U.S. automobile imports: historical and projected.

Petroleum Savings

Because ceramic components will allow even conventional engines (Otto and diesel) to operate at higher-than-normal temperatures and thus greater thermal efficiency, fuel savings will begin with the introduction of the first ceramic-component vehicles. However, energy savings between 1985 and 1990 will be negligible for two reasons. First, the moderate level of sales means that ceramic-engine vehicles will take some time to become a significant portion of the total vehicle stock. Second, because of higher investment in ceramic-related expenditures (e.g., new engine assembly lines), the economy is on a moderately expansionary course concurrent with a slightly greater demand for energy. However, as the stock of vehicles with ceramic-engine components builds up and advanced engines are introduced in 1990, fuel savings will begin to increase at a faster rate. The total petroleum savings will be nearly 0.1 quad by 1995, 0.25 quad by 2000, and 1.1 quads by 2005. One quad ($10^{15}$ Btu) is the equivalent of 8 billion gal of gasoline.

The energy savings in the Japanese dominance case will be minor compared with total petroleum use, principally because of the import restrictions assumed in this case. Direct vehicle energy savings will eventually climb to 0.06 quad by the year 2005. However, the decline in domestic vehicle production will push the economy to lower levels so that total energy demand will decrease. Annual fuel savings will peak in this scenario in 1995 at 0.3 quad. As the GNP gap between this case and the base case narrows, leading to a relatively greater demand for energy, total fuel savings will shrink to 0.2 quad by the year 2000 and 0.1 quad by 2005.

Gross National Product

The economy performs better under the U.S. dominance case than in the base case because this technology alternative is expansionary. Figure 2 illustrates the changes in GNP that could be expected in the scenarios. In the U.S. dominance case, real GNP (in constant 1981 dollars) will peak in the year 2000 at about $28 billion higher than in the base case. The high growth rates in the early stages are inflationary, creating a dampening effect on the economy in the latter periods. These cyclic effects will reduce GNP gains after the year 2000 as the economy tends to return to its original, unperturbed path. Cumulative real GNP gains will approach $280 billion (1981 dollars), which indicates a sizable economic contribution from the ceramic technology.

Real GNP follows a lower trajectory in the Japanese dominance case than in the base case projections. Annual loss in GNP will be greatest in 1995, with a decline of more than $11 billion (1981 dollars). After that, the long-run equilibrium forces

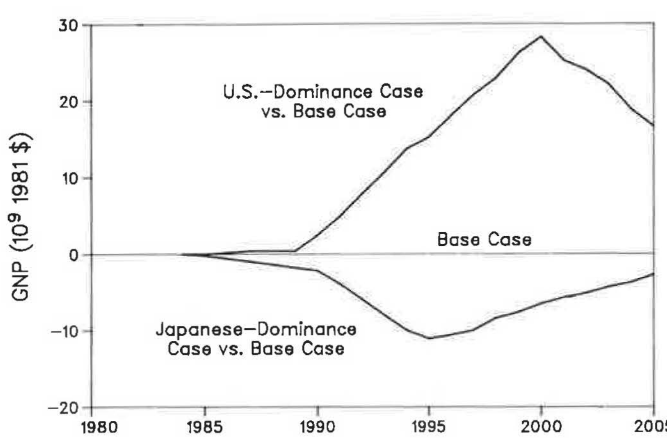


FIGURE 2 Changes in gross national product under the alternative scenarios.

in the economy will narrow the gap to about $3 billion by 2005. Imported automobiles will be sold at the expense of domestic models, shifting production to Japan and thus reducing GNP. The cumulative GNP loss between 1985 and 2005 is $110 billion (1981 dollars) more than in the base case.

## Employment

Each of the scenarios can be expected to have significant effects on employment because of the large labor requirements of automobile manufacturers and their suppliers. In the U.S. dominance case, total employment will increase by 25,000 in 1990, nearly 175,000 in 1995, and 250,000 in 2000, relative to the base case. The rate of change in employment would cause the projected national unemployment rate to drop from 6.5 percent in the base case to 6.3 percent in the U.S. dominance case by the year 2000.

The Japanese dominance case, because of its lower level of U.S. economic activity, has lower employment levels. Compared with that in the base case, U.S. employment will decline until the loss of jobs reaches 106,000 by 1995. With trade restrictions stabilizing the level of imports of ceramic engine automobiles at 500,000 annually, the job loss will bottom out in that year.

## Balance of Trade

Successful commercialization of structural ceramics in motor vehicles in the U.S. dominance case will improve U.S. balance of trade accounts in two distinct ways. Fewer imported automobiles will be purchased and, as the stock of more fuel-efficient vehicles increases, oil imports will decline. In the Japanese dominance case, the increase in imported automobile sales will offset the reduced imports of fuel. Total import savings in the year 2005 will reach $27.7 billion (1981 dollars) in the U.S. dominance case, but will be a negative $5.5 billion (1981 dollars) in the Japanese dominance case.

As indicated, a substantial portion of the total import savings will come from the projected reduction in petroleum demand that could be achieved with more efficient engines using ceramic components. Almost half of the import savings in the U.S. dominance case will be due to savings in imported petroleum--$10.2 billion (1981 dollars) in the year 2005. Restrictions on imported ceramic-engine automobiles in the Japanese dominance case will limit the fuel component of import savings to $0.6 billion (1981 dollars) for the same year.

## STRATEGIC MATERIALS

Some analysts believe that U.S. dependence on foreign strategic mineral resources is far more serious than the reliance on foreign petroleum supplies. Strategic or critical materials are those that (a) the United States must chiefly import (especially if the deposits are in communist countries or in countries whose governments are unstable) and/or (b) are scarce. Structural ceramics are candidates to replace a wide variety of strategic materials, particularly those used as superalloys.

Table 2 (18) lists several strategic materials that are currently used in high-temperature applications and engine systems and that could be replaced by structural ceramics. Demand for many of these materials, despite their high costs, is expected to increase substantially between now and the end of the century. These metals generally have high strength and light weight, and can be used in alloys. However, their desirable properties are overshadowed by economic considerations when the large volumes necessary for use in vehicle engines are contemplated. The fact that so much of this material comes from potentially unstable suppliers (such as South Africa, the USSR, Zimbabwe, and Turkey) simply compounds the difficulties of using these metals in a mass market.

**TABLE 2 Characteristics of Selected Strategic Materials *(18)***

| Mineral | Range of Imports, 1975-1980 (%) | U.S. Vulnerability to Foreign Disruptions | Major Source |
|---|---|---|---|
| Beryllium | Not available | No | Brazil, South Africa |
| Cobalt | 100 | Yes | Zaire, Zambia |
| Chromium | 90-100 | Yes | South Africa, USSR, Turkey, Zimbabwe |
| Manganese | 98 | Yes | Gabon, Brazil, South Africa |
| Nickel | 70-80 | Possibly | Canada, New Caledonia, Dominican Republic, Australia |
| Columbium | 100 | Yes | Brazil, Thailand, Canada |
| Tantalum | 98 | Yes | Thailand, Canada, Australia, Brazil, Zaire |

## CONCLUSIONS

Commercialization of structural ceramics in heat engines will have a wide range of benefits for both manufacturers and consumers. Ceramic materials are critical in the development of several advanced engines for motor vehicles, including the adiabatic diesel, the gas turbine, and possibly the Stirling engine. These engines should achieve a 25 to 35 percent improvement in fuel efficiency compared to conventional Otto-cycle or diesel engines. Even in conventional engines, selected ceramic components should reduce heat loss and increase thermal efficiency to improve fuel economy by 5 to 15 percent or perhaps more.

What this improved engine efficiency means in terms of national energy savings depends, of course, on the market success of the vehicles with these engines. As shown by one scenario in this analysis, the annual fuel savings for the nation could be in the billions of gallons of gasoline within a few years of market penetration by these vehicles. More difficult to quantify, yet nonetheless realistic, is the ability of these engines to use alternative fuels. In the event of escalating petroleum prices or shortages of petroleum-derived fuels, the use of alcohol fuels or, in the longer term, synthetic fuels, is feasible with these engines.

Major economic benefits will accrue to the nation that first commercializes structural ceramics, especially if that nation is able to dominate a market as large as that of motor vehicle engines. Gross national product should rise significantly relative to the research and development investment in ceramics, and employment should increase concurrently. Favorable balance-of-trade changes should also be expected as automobile and fuel imports are reduced.

The development of reliable structural ceramics in motor vehicle engines should also reduce the nation's dependence on several strategic materials. Beryllium, cobalt, chromium, manganese, nickel, columbium, and tantalum have uses in heat engines and other high-temperature applications. Because these materials either are sufficiently scarce or come from countries that could be considered unreliable suppliers, the United States stockpiles these metals. Advanced ceramics could replace alloys of these materials in many applications.

Although this analysis was limited to the use of structural ceramics in vehicular engine systems, the research needed to develop such advanced ceramics will also produce ceramics with applications in other product areas. The economic benefits from these other commercial uses may be quite substantial, and additional energy savings may also result from some of these uses.

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