Evaluation of the Advanced Ceramics Market for New Applications of Three Dimensional Printing

by

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B.S., Mechanical Engineering
Tulane University
(1992)

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science at the Massachusetts Institute of Technology May 1995

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Chariman, Graduate Committee
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ABSTRACT

Three Dimensional Printing is a process for the manufacture of tooling and functional prototype parts directly from computer models. Three Dimensional Printing functions by the deposition of powdered material in layers and the selective binding of the powder by "ink-jet" printing of a binder material. Following the sequential application of layers, the unbound powder is removed, resulting in a complex three-dimensional part. The process may be applied to the production of metal, ceramic, and metal-ceramic composite parts.

Accomplishments of this effort are the development of interactive database and spreadsheet tools for evaluating new 3DP applications, selection of an application for further analysis using software methods, and creation of fully dense, complex 3DP ceramic composites via liquid melt infiltration techniques to demonstrate 3DP's ability to compete in this market.

Interactive database and spreadsheet tools were developed around the Quality Loss methodology to evaluate the technical and financial feasibility of new applications for 3DP. The Quality Loss methodology developed here is a quantitative method of comparing the capabilities of a manufacturing process with the design specifications of a given application. This software has been used to analyze the characteristics of 89 potential 3DP applications and rank them from most to least promising. From these applications, the compact core high temperature heat exchanger was chosen as the most appealing application of 3DP under the given circumstances. Other top applications are discussed in detail.

Up to the beginning of this project, only simple fully dense ceramic 3DP components without internal cavities had been created via isostatic pressing and sintering. Liquid melt glass-ceramic infiltration techniques were explored and alumina (Al₂O₃) preforms have been successfully densified in creating the first fully dense, complex 3DP components with very little overall shrinkage.

Based on experience gained in the market study and test component fabrication phases of the 3DP Application Survey, suggestions for the possible evolution of 3DP are made. Machine and process enhancements to make 3DP a viable manufacturing process for full production of structural ceramics are briefly explored.

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1 INTRODUCTION

This thesis is the culmination of a two year cooperative effort between the Three Dimensional Printing Project (3DP) at the Massachusetts Institute of Technology and Charles Stark Draper Laboratories. Draper Labs, in addition to its role as a member of the 3DP Industrial Consortium, supports this work financially, and with expertise in engineering and market analysis.

Known internally as the 3DP Application Survey, this work is a broad ranging study including elements of marketing, materials science, and mechanical engineering. Goals of the project are to: 1) survey the advanced ceramics market 2) develop software tools to evaluate new applications of 3DP, 2) fabricate and test components representing the market selected by the analysis software, and 3) suggest and, time permitting, implement process enhancements which increase the marketability of 3DP.

Accomplishments of this effort are: a review of worldwide advanced ceramic markets, the development of interactive database and spreadsheet tools for evaluating new 3DP applications, selection of an application for further analysis using software methods, and creation of fully dense, complex 3DP ceramic composites.

1.1 Ceramics Market-

Advanced ceramics continue to receive much attention as researchers push the envelope of material capabilities in the automotive, aerospace, chemical, electronics, and material processing industries. Worldwide markets are expected to exceed $20 billion by the year 2000 for all technical ceramics, with the strongest growth in the relatively small structural ceramics segment. Although researchers are reporting gains in many areas, the general feeling is that structural ceramics processing techniques are not yet mature enough for mass production. A very distinct need for more reliable, and flexible ceramic forming processes for structural ceramics exists, emphasizing the potential of 3DP.
1.2 Software Tools

To aid in managing data on numerous potential applications of 3DP, interactive database and spreadsheet tools were developed in Lotus Approach and Microsoft Excel. The primary function of these tools is to organize the engineering characteristics of 89 applications and compare them with the capabilities of current and future 3DP printers. The basis of these tools is the Quality Loss Function suggested by M. Phadke which places a numeric value on how deviations from specified engineering targets affect the overall quality of a product. For this project, Quality Loss has been applied in a novel way: to evaluate 3DP’s potential for fabricating advanced ceramic components. From the group of candidate applications, the compact core high temperature heat exchanger was chosen as the most promising application of 3DP which could also be handled within the confines of this project. Other top applications are discussed in detail.

The software tools developed for the 3DP Application Survey are themselves potentially marketable products, addressing a need in the engineering community for intuitive software-based design aids. In a more refined form they have the potential to educate designers of how 3DP can help them quickly and inexpensively iterate towards an optimal design.

1.3 Process Enhancements -

In order to compete in the rapidly growing structural ceramics market against traditional ceramic forming processes, new methods of densifying complex 3DP ceramic preforms are necessary. Until this project, only simple fully dense ceramic 3DP components without internal cavities had been created via isostatic pressing and sintering the printed preform. It was necessary to eliminate the isopressing step because it requires that the preform be encased in a conformal fluid barrier during the compaction operation, greatly limiting the range of acceptable geometries. Secondly, isopressing and sintering of 3DP preforms causes drastic shrinkage from green to final part. Therefore, a new methodology
for making ceramic composite components with 3DP preforms was explored: liquid melt infiltration.

Liquid melt glass-ceramic infiltration of alumina (Al₂O₃) preforms has been successful in creating the first fully dense, complex 3DP components with very little overall shrinkage. This is an important milestone for 3DP because it greatly increases the number of possible applications. An added benefit of the melt infiltration technique is the ability to tailor the final material properties of the ceramic composite to match the requirements of a given application by controlling composition and amount of infiltrant.

Based on experience gained in the market study and test component fabrication phases of the 3DP Application Survey, suggestions as to the possible evolution of 3DP are made. 3DP remains in its commercial infancy, with Soligen and fledgling Z-Corporation making the first steps towards capturing portions of the Rapid Manufacturing and Rapid Modeling markets respectively. There remain, however, several market segments yet to be addressed, the direct metal parts and direct ceramic parts to name just two. The section devoted to the evolution of 3DP is designed to discuss possible machine and process enhancements to make 3DP a viable manufacturing process for full scale production of components for these other markets. Work already done in the area of printhead development is discussed.

1.4 Document Organization -

Organization generally follows the timeline of the 3DP Application Survey through its different phases: Market Survey, Development of Software Tools, Selection of a Candidate Application, and Process Improvements. Each section is followed by a summary and concluding remarks. A graphic similar to the one on the following page is included at the beginning of each chapter to guide the reader from section to section, and add continuity.

The remainder of Chapter 1 is a general overview of the Three Dimensional Printing process. Chapter 2 summarizes results of the advanced ceramics market survey and
comments on which segments are the most promising for 3DP. Chapter 3 describes the software tools developed to help select new 3DP applications. Chapter 4 describes the applications included in the survey and gives detailed information on the top applications selected by the software tools. Chapter 5 covers process improvements in the areas of materials, process, and hardware.

1.5 Introduction to Three Dimensional Printing -

Invented at MIT by Professors Emanuel Sachs and Michael Cima, Three Dimensional Printing is a process for the manufacture of tooling and functional prototype parts directly from computer models. Three Dimensional Printing functions by the deposition of powdered material in layers and the selective binding of the powder by
Three Dimensional Printing Process

Create Solid Model of Component in CAD

Slice Solid Model Into 2-D Layers

3D Printing

Spread Powder

Print Layer

Drop Piston

Repeat Cycle

Remove Excess Powder

Post Processing
"ink-jet" printing of a binder material. Following the sequential application of layers, the unbound powder is removed, resulting in a complex three-dimensional part. The process may be applied to the production of metal, ceramic, and metal-ceramic composite parts.39

1.5.1 Materials Capabilities

3DP has demonstrated its flexibility in fabricating complex components out of advanced ceramics and stainless steel. Ceramic materials include Alumina (Al2O3), Zirconia Toughened Alumina (ZTA), Silicon Nitride (Si3N4), and glass-ceramics of the Lanthanum-Alumina-Silicate family as an infiltrant. Of these, alumina has received the most attention due to its wide applicability. Metal parts include 316L and 440C stainless steels, tungsten carbide/cobalt and titanium carbide reinforced metal matrix composites.40

1.5.2 Geometry

In addition to materials flexibility, 3DP can produce components of arbitrary geometry, both external and internal. Examples of 3DP’s capabilities, and specifics on the 3DP process are handled in other sections of this thesis. The component below is just one example of a complex ceramic component fabricated on MIT’s alpha machine. Design, printing (in 30μm platelet alumina and colloidal silica binder), and firing to 40+% density required approximately 24 hours total time. It measures 22.8 x 3.3 x 3.3 cm with complex internal geometries. Fabricating this component by traditional means would require several
steps and substantially more time.

1.5.3 Commercial Applications

The 3DP technology has been licensed to Soligen, Inc. North Ridge, CA and Therics Inc., New York, NY for fabricating investment casting shells and medical devices respectively. Soligen has constructed alpha and beta versions of its DSP system (described in section 2.7) but its primary business is creating metal casting shells for clients. Therics, a small start-up company with offices in New York and Boston, has a license allowing the direct fabrication of medical devices and drug delivery systems, via 3DP.
2 Survey of the Advanced Ceramics Market

The initial focus of the 3DP Application survey is to gain an understanding of the advanced ceramics market both present and projected. Results of this survey are used to narrow the search for new 3DP applications to a more manageable range.

APPLICATION ANALYSIS
PROCESS
1. Literature Search and Interviews

Figure 2.1

This section gives an overview of the advanced ceramic markets as of late 1994, broken down by geographic region and market segment. Information was gathered from journal articles and recent publications in the areas of advanced materials, design, marketing, and industrial forecasting. The second major portion of this section is an overview of current ceramics manufacturing processes, highlighting their strength and limitations.

2.1 Definition of Advanced Ceramics

It is perhaps useful to first give a brief definition of what exactly "advanced" ceramics are. According to Schwartz, advanced, technical, high-performance, or fine ceramics are generally characterized as being held together by covalent bonding, ionic bonding or a combination of both. Covalently bonded materials exhibit high hardness, superior chemical inertness, no ductility, low thermal expansion, and low electrical conductivity. Ionic bonded ceramics demonstrate low ductility, high thermal expansion, and
low electrical conductivity. In general ceramics have high melting temperatures, high stiffness, high strength at elevated temperature, high compressive strength, excellent wear and corrosion resistance and low density.

Areas where advanced ceramics are typically employed are shown in Figure 2.2 below. As can be seen, the spectrum of possible applications for advanced ceramics is quite broad, touching nearly every aspect of modern engineering.

![Diagram of Ceramic Applications](image)

Figure 2.2

Typical material properties for a few of the more ubiquitous ceramic varieties is given in Table 2.1. As can be seen, ceramics possess a wide array of characteristics which can often be tailored to the specific needs of a particular application.
Table 2.1 Properties of Typical Engineering Ceramics (Coors Ceramic Co.)

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength (MPa)</th>
<th>E (GPa)</th>
<th>Failure Strain (%)</th>
<th>Density (g/cc)</th>
<th>Max. Use. Temp C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>240</td>
<td>410</td>
<td>0.06</td>
<td>3.1</td>
<td>1,200</td>
</tr>
<tr>
<td>Si₃N₄</td>
<td>675</td>
<td>310</td>
<td>0.22</td>
<td>3.31</td>
<td>1,650</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>240</td>
<td>345</td>
<td>0.08</td>
<td>3.89</td>
<td>1,750</td>
</tr>
<tr>
<td>Steel</td>
<td>550</td>
<td>205</td>
<td>5-10.00</td>
<td>7.5-8</td>
<td>760</td>
</tr>
</tbody>
</table>

Ceramics offer high strength at temperatures beyond the useful temperature of metals, they have low densities, high hardness, corrosion resistance, high stiffness, and are generally excellent electrical insulators at room temperature. Ceramics are typically brittle, and exhibit catastrophic failure, although new ceramic compositions including fibrous reinforcements are showing that ceramics can be made relatively tough. Because most ceramics are comprised of common, easily obtained constituents, they offer an alternative to rare metal compounds for many high tech applications. This reduces the reliance on foreign sources for strategic materials.

2.2 Ceramics Market Introduction

Advanced Ceramics is a dynamic, multi-billion dollar industry which will continue to grow at a modest rate well into the next century. Industrial nations around the world have recognized the great potential of advanced ceramics, and the necessity to poise themselves to take full advantage as this technology matures. Japan, Germany, the United States, and other industrial nations are actively funding basic and applied advanced ceramics research, foreseeing future payoffs in greater market share for their industries (see Figure 2.3).

Ceramics are technically superior to traditional materials in many electrical, mechanical, optical, and thermal applications, and hold the promise to become cost competitive as manufacturing processes are improved. The impetus is now upon overcoming ceramics' inherent material limitations, increasing designers' and manufacturers'
awareness of how to properly implement and process advanced ceramics. Industry has also realize that to be competitive in an aggressive world market an infrastructure of "strategic partnerships" to develop close cooperation between the raw material supplier, shape producer and equipment manufacturer will be necessary.\textsuperscript{17}

There remains, however, considerable friction in certain industry segments to invest heavily in ceramics. Short term profit goals, uncertain material and manufacturing characteristics, and, most importantly, costs cause many companies to shy away from ceramics until they are better understood\textsuperscript{18}. The automobile industry is one such area. Car manufacturers have been intimately involved in ceramics research for over a decade hoping to reap the benefits ceramics offer, but have allowed only relatively low numbers of ceramic components find their way into cars\textsuperscript{18}.

Despite these doubts analysts are confident that advanced ceramics will continue to gain in importance and market share, and will be one of the key industries of the 21\textsuperscript{st} century.

\textbf{2.3 Worldwide Markets -}
Although there is considerable discrepancy as to the exact value of the worldwide advanced ceramics market, one fact is certain: the market is growing healthily and is expected to continue to grow through the year 2000. The Fredonia Group's study indicates that the advanced ceramic market will grow at 8.7% annually, reaching $20 billion by 1997.1 Tables 1 and 2 show two further views on the status of the global ceramics market and indicate trends for growth of the various segments.

Table 2.2: Present Size of the Fine Ceramics Market and Estimated Size in 2000

<table>
<thead>
<tr>
<th>Item</th>
<th>1,987 (100 million Yen)</th>
<th>2,000 (100 million Yen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic Parts</td>
<td>7,400</td>
<td>28,870</td>
</tr>
<tr>
<td>Tools and Mechanical parts</td>
<td>1,000</td>
<td>5,040</td>
</tr>
<tr>
<td>Thermal Parts</td>
<td>500</td>
<td>4,940</td>
</tr>
<tr>
<td>Parts of Chemical and Medical Equipment</td>
<td>620</td>
<td>4,510</td>
</tr>
<tr>
<td>Optical Parts</td>
<td>920</td>
<td>7,150</td>
</tr>
<tr>
<td>Other Parts</td>
<td>200</td>
<td>4,650</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10,640</strong></td>
<td><strong>55,160</strong></td>
</tr>
</tbody>
</table>

*Note that the exchange for Yen is approximately 100 to $1

Table 2.3 Worldwide Ceramic Consumption Estimates

<table>
<thead>
<tr>
<th>Ceramic</th>
<th>$ billion, 1992</th>
<th>Growth, 1992-2000, %/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electronic</td>
<td>4.0 - 9.0</td>
<td>7 - 11</td>
</tr>
<tr>
<td>Structural</td>
<td>1.2 - 2.0</td>
<td>6 - 10</td>
</tr>
<tr>
<td>Coating/Service</td>
<td>0.8 - 1.7</td>
<td>9 - 11</td>
</tr>
<tr>
<td>Composite</td>
<td>0.1 - 0.3</td>
<td>13 - 15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.1 - 13.0</strong></td>
<td>--</td>
</tr>
</tbody>
</table>
Experts agree that although the electronic advanced ceramics market will continue to be the largest and most mature market, the structural ceramics market is the fastest growing.

Looking at individual countries' involvement gives a better perspective on who the major players are in the global ceramic market. Figure 2.3 above shows the relationship between the Japanese, the leading producer of advanced ceramics (called fine ceramics in Japan), the United States, and the other top ranked nations.

2.3.1 Japan

It is clear that the Japanese have a distinct advantage in the market, due in large part to government supported research and industrial strategic partnerships. "Some say the United States is the leader in high-performance ceramics R&D, while Japan is the leader in applications development. Others say the U.S. is maintaining its competitive position in CMCs and MMCs, but losing in monolithic ceramics." Table 2.4 depicts the development of the Japanese advanced ceramic market over a 7 year period. Structural (mechanical) ceramics made the greatest advances, going from $269 million in 1983 to $1,416 million in 1990, a 526% growth over this period.

<table>
<thead>
<tr>
<th>Year</th>
<th>Elect. - magnet</th>
<th>Mechanical</th>
<th>Optical</th>
<th>Chemical</th>
<th>Thermal</th>
<th>Misc.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>3,957</td>
<td>269</td>
<td>119</td>
<td>206</td>
<td>183</td>
<td>55</td>
<td>4,793</td>
</tr>
<tr>
<td>1986</td>
<td>4,287</td>
<td>681</td>
<td>399</td>
<td>415</td>
<td>326</td>
<td>16</td>
<td>6,123</td>
</tr>
<tr>
<td>1989</td>
<td>5,159</td>
<td>1,276</td>
<td>386</td>
<td>446</td>
<td>419</td>
<td>27</td>
<td>7,712</td>
</tr>
<tr>
<td>1990</td>
<td>5,473</td>
<td>1,416</td>
<td>429</td>
<td>460</td>
<td>465</td>
<td>33</td>
<td>8,276</td>
</tr>
</tbody>
</table>

According to Kimura and Gregory, the rationale behind the high levels of financial and organizational support the Japanese government is committing to high performance structural ceramics is a consequence of the following points:

---

Structural ceramics can be either monolithic or composite in nature. Composite ceramics include toughened ceramics such as Zirconia Toughened Alumina (ZTA) and whisker or fiber reinforced ceramics.
High-performance ceramics will require less imported raw material and fuel per unit product than other materials technologies

- High-performance ceramics are high-value-added products
- High-performance ceramics products are generally small and light-weight. Thus they can be shipped by air. This means that industries can be developed in the interior of Japan without population growth problems being imposed on the already overcrowded coastal port cities.
- The enabling feature of ceramics as components in systems can increase market penetration and export sales

Funatani estimates that Japanese manufacturers will command 44% of the world's projected $20 billion electronic advanced ceramics market in the year 2000. Unless greater initiative is taken on the part of American industry and government alike, the United States will continue to walk in the shadow of the Japanese in this key technology.

2.3.2 Korea -

In recent years Korea has stepped forward to join Japan, Taiwan, and Hong Kong as an important economic power in southeast Asia, becoming the world's 5th leading manufacturer of electronic products. As with Japan, Korea has been very active in assuring a place at the table in the advanced ceramics market, representing about an eighth of the U.S. market volume, and nearly half of that of Germany. The majority of Korea's advanced ceramics are produced in small and medium industrial companies lacking the capacity to meet the needs of an expanding market. Therefore the Korean government has earmarked $1.5 billion in 1991 to modernize production facilities. Table 2.5 gives an overview of Korea's advanced ceramic activities.

---

An enabling technology is one in which a small amount of material (as a critical component) or a subsystem (as in an integrated circuit) adds so much additional capability that major advances, as opposed to incremental changes, result.
Table 2.5: Demand and Production of Advanced Ceramics in Korea

<table>
<thead>
<tr>
<th>Items</th>
<th>Demand</th>
<th>Production</th>
<th>Demand</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>1991</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural &amp; Wear</td>
<td>15.8</td>
<td>4.4</td>
<td>57.7</td>
<td>23.9</td>
</tr>
<tr>
<td>Insulators - IC packages, substrates, resistors, etc</td>
<td>103.3</td>
<td>4</td>
<td>153.2</td>
<td>97.9</td>
</tr>
<tr>
<td>Capacitors - disk, MLCC, B-L, F-T, etc</td>
<td>83.2</td>
<td>41.6</td>
<td>194.1</td>
<td>117.9</td>
</tr>
<tr>
<td>Piezoelectrics - filters, quartz, buzzer, ignitors, etc</td>
<td>46</td>
<td>8</td>
<td>137.4</td>
<td>59.3</td>
</tr>
<tr>
<td>Ferrites - soft, hard, magnetic heads</td>
<td>227.7</td>
<td>94.2</td>
<td>328.4</td>
<td>136.1</td>
</tr>
<tr>
<td>Semiconducting</td>
<td>34</td>
<td>2.8</td>
<td>61.3</td>
<td>18.4</td>
</tr>
<tr>
<td>Total</td>
<td>494.2</td>
<td>155</td>
<td>932.1</td>
<td>453.5</td>
</tr>
</tbody>
</table>

2.3.3 China and Malaysia -

Both China and Malaysia are active in materials research and are expected to be important contributors to the world ceramics market in the next century. "In contrast to most other countries, demand for refractories in China should grow, as steel production has continued to increase from 37 MT in 1980 to 80 MT in 1992." Asia in general represents the area of greatest growth potential in nearly all areas of high technology, advanced ceramics included. It can be expected that equipment and technology sales to and from this region will continue to be a lucrative market for the foreseeable future.

Europe is less dynamic than the east, but when considered as a single economic unit, represents roughly a sixth of the world's total advanced ceramics markets. Germany is Europe's leader in advanced ceramics with strong industrial and government support of basic and applied materials research. German researchers are concentrating on engine components, isostatic pressing, silicon nitride gas turbine components, wear, biomedical and cutting tool applications. After Germany, the Italians continue to show interest in ceramics,
with the French and English playing lesser roles. It should not be forgotten that the European Economic Community represents an enormous market for high technology goods and services, as well as a major competitor to the U.S.

2.4 U.S. Markets -

The United States is the world's second largest producer of advanced ceramics goods after Japan. A breakdown of the American market is given in Table 2.6. Electronic ceramics again represent the largest market segment ($3.4 billion), but structural ceramics are growing at the fastest rate (13% annually). Areas of greatest research activity are electronics substrates and packaging (MMCs), heat engine applications (adiabatic diesel, spark ignition and gas turbine components), wear applications (automobile, paper, textile industries), high temperature applications (heat exchangers), biomedical applications, superconducting materials, and corrosive environment applications (chemical industry).

<table>
<thead>
<tr>
<th>Market Segment</th>
<th>1992</th>
<th>2000</th>
<th>% Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>385</td>
<td>1,020</td>
<td>13</td>
</tr>
<tr>
<td>Electronics</td>
<td>3,400</td>
<td>6,500</td>
<td>8.5</td>
</tr>
<tr>
<td>Coatings</td>
<td>445</td>
<td>940</td>
<td>9.8</td>
</tr>
<tr>
<td>Total Market</td>
<td>4.2</td>
<td>8.4</td>
<td>9.1</td>
</tr>
</tbody>
</table>
Pathfinder Operations (Lancaster, PA) forecasts in their report "Structural Ceramics in the United States" the American ceramics market will grow at a 6.7% annual rate through 1996. Furthermore, Pathfinder states that structural ceramics will show the greatest gains, albeit in ceramic-matrix composites and coatings rather than monolithic components. This is a somewhat more conservative estimate compared to the BCC forecast mentioned above, reflecting perhaps that the development of ceramic heat engine components has been slower than anticipated.

As defense spending continues to dwindle, materials manufacturers are shifting their focus to the private sector, hoping to develop new applications for advanced materials. Aiding in this transition are several initiatives supported by both the government and industry. Research and development spending in the United States, although it has seen only minor increases in recent years, continues to be strong. Table 2.7 is an overview of U.S. dollars earmarked for R&D for 1994.

<table>
<thead>
<tr>
<th>Research Sector</th>
<th>Funding</th>
<th>% of Total</th>
<th>Spending</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry</td>
<td>$84.9</td>
<td>51.6</td>
<td>$114.8</td>
<td>69.9</td>
</tr>
<tr>
<td>Federal</td>
<td>$69.7</td>
<td>42.4</td>
<td>$16.8</td>
<td>10.2</td>
</tr>
<tr>
<td>Academic</td>
<td>$6.4</td>
<td>3.9</td>
<td>$26.7</td>
<td>16.2</td>
</tr>
<tr>
<td>Other</td>
<td>$3.5</td>
<td>2.1</td>
<td>$6.2</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>164.5</strong></td>
<td><strong>100</strong></td>
<td><strong>164.5</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Additionally, increased use of advanced ceramics will reduce the United States' dependence upon other nations for rare materials required in many high-tech components. This is of great importance to defense related industries.

In general, the advanced ceramics market in the United States is growing at somewhere between 6% and 10% annually towards a total value over $1 billion by the year
2000. Structural ceramics, especially composites and coatings, are expected to have the greatest growth.

2.5 Specific Markets

This section outlines trends and applications in the electronics and structural ceramics markets, the largest and fastest growing respectively.

2.5.1 Structural Ceramics -

As mentioned previously, structural ceramics is the fastest growing segment of the advanced ceramic market. Table 2.8 breaks the worldwide structural ceramics market into its constituent segments with their corresponding values.

| Table 2.8: Worldwide Market Projections for High Performance Structural Ceramic Parts$^{20}$ |
|---------------------------------|----------|----------|----------|
| Application                     | 1935     | 1995     | 2005     |
| Heat Engine Ceramics            | 30       | 1,000    | 4,000    |
| Bearings                        | Negligible | 200     | 400      |
| Cutting tools and metal working | 75       | 150      | 300      |
| Industrial wear parts           | 300      | 450      | 900      |
| Biomedical and dental including crown | 1,000 | 2000    | 4,000    |
| Total                           | 1,405    | 3,800    | 9,600    |

2.5.1.1 Biomedical -

Interestingly, biomedical applications at $1.0$ billion were responsible for 71% of the structural ceramics market in 1985. In 1995 and 2005, biomedical sales will still total 53% and 42% of the market respectively. Following is a list of present uses of bioceramics:$^{29}$

- Orthopedic load-bearing applications
- Coatings for chemical bonding
- Dental implants
- Alveolar ridge augmentations
• Otolaryngological applications
• Artificial tendons and ligaments
• Coatings for tissue ingrowth
• Temporary bone space fillers
• Periodontal pocket obliteration
• Maxillofacial reconstruction
• Percutaneous access devices
• Orthopedic fixation devices

Ceramics' excellent resistance to corrosive environments gives it an innate advantage in biomedical applications where other materials are unsuitable. New ceramics manufacturing methods such as MIT's Three Dimensional Printing (3DP) promise to open even more avenues for novel bioceramic applications. Obviously as medical and materials research advances, there will be even greater use of advanced materials in biomedical applications.

2.5.1.2 Heat Engines -

The second, and perhaps more interesting market segment to investors looking for growth industries, are heat engine applications. Worldwide sales in this area are expected to explode from $30 million in 1985 to $4 billion by 2005. Other experts, however, are skeptical that this magnitude of growth is possible. As previously mentioned, the development of ceramic heat engine components has been slower than anticipated.

2.5.1.3 Automotive Engines-

Advanced structural ceramic components for internal combustion engines are envisioned as a means to increase efficiency, reduce emissions, and increase power density. Ceramics offer better high temperature performance, reduced wear and lower density when compared to their metal counterparts. Components under evaluation include:

- Roller follower
- Turbo rotor
- Valves
- Heads (composite coating)
- Piston (composite coating)
- Piston Rings (coating)
- Injector link
- Piston Head (ceramic composite)
- Port liner (coating)
- Injector plunger

Tables 2.9 and 2.10 are the results of interviews with industry experts in Light-, Medium-, and Heavy-duty engine development, indicating benefits and barriers to the use of structural ceramics in these applications. In both areas (Medium&Heavy and Light), cost was the overriding hindrance to more widespread acceptance of ceramic components. Even with a five times reduction in component cost, 33% of responding engineers in Medium&Heavy-duty engine development felt that no engine component would benefit from the use of ceramics (not shown in table).  

### Table 2.9: Perceived Benefits and Barriers To the Use of Ceramics in Medium to Heavy Duty Engine Applications

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Respondents (out of 80)</th>
<th>Barriers</th>
<th>Respondents (out of 80)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear</td>
<td>57 (71%)</td>
<td>Cost</td>
<td>63 (79%)</td>
</tr>
<tr>
<td>Thermal props</td>
<td>44 (55%)</td>
<td>Manufacturability</td>
<td>34 (43%)</td>
</tr>
<tr>
<td>Emissions</td>
<td>34 (43%)</td>
<td>Limited Supply Base</td>
<td>33 (41%)</td>
</tr>
<tr>
<td>Corrosion</td>
<td>20 (25%)</td>
<td>Brittle</td>
<td>30 (38%)</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>20 (25%)</td>
<td>Producing quality parts reliably</td>
<td>24 (30%)</td>
</tr>
<tr>
<td>Weight Reduction</td>
<td>18 (23%)</td>
<td>Unproven durability</td>
<td>22 (28%)</td>
</tr>
<tr>
<td>Reduced inertia</td>
<td>18 (23%)</td>
<td>Industry resistant to change</td>
<td>14 (18%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inadequate guidelines</td>
<td>8 (10%)</td>
</tr>
</tbody>
</table>

### Table 2.10: Perceived Benefits and Barriers To the Use of Ceramics in Light Duty Engine Applications

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Respondents (out of 95)</th>
<th>Barriers</th>
<th>Respondents (out of 95)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions</td>
<td>42 (44%)</td>
<td>Cost</td>
<td>72 (75%)</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>43 (42%)</td>
<td>Manufacturability</td>
<td>52 (54%)</td>
</tr>
<tr>
<td>Thermal properties</td>
<td>33 (34%)</td>
<td>Unproven durability</td>
<td>51 (53%)</td>
</tr>
<tr>
<td>Wear</td>
<td>32 (33%)</td>
<td>Industry Resistant to change</td>
<td>44 (46%)</td>
</tr>
<tr>
<td>Increased power density</td>
<td>29 (30%)</td>
<td>Producing quality parts reliably</td>
<td>38 (40%)</td>
</tr>
<tr>
<td>Weight Reduction</td>
<td>23 (24%)</td>
<td>Brittle</td>
<td>37 (39%)</td>
</tr>
<tr>
<td>Reduced inertia</td>
<td>15 (16%)</td>
<td>Limited Supply Base</td>
<td>34 (35%)</td>
</tr>
<tr>
<td>Corrosion</td>
<td>10 (10%)</td>
<td>Inadequate guidelines</td>
<td>12 (13%)</td>
</tr>
<tr>
<td>None</td>
<td>20 (21%)</td>
<td>Better alternate materials</td>
<td>10 (10%)</td>
</tr>
</tbody>
</table>

Advances in manufacturing techniques have not yet met the demand for quality parts possessing highly predictable characteristics. This reduces companies' willingness to risk incorporating ceramic components into large production volume systems. This is not to say that structural ceramics have not been employed in such systems: a total of some 6.4 million structural ceramic components (not including sparkplugs or headlamp fixtures) were installed in Japanese automobiles in 1991. However, one ceramics manufacturer states "as long as the cost is high, ceramics will be low on the priority list . . . but as soon as the cost goes down, more testing will be done and we can get at the real problems regarding durability, brittleness, and reliability"

Another area where the existing structural ceramics industry is lacking: production capacity. Currently there is far too little production capacity to meet projected demands of the auto industry. This is related to the high costs and uncertainty associated with fabricating advanced ceramic components. "Domestic markets are sometimes too small to generate the necessary income and profits to justify the investment in R&D or business entry."

Material limitations are cited by some engineers as the underlying reason for structural ceramics slower than expected acceptance for automotive applications. "Historically, new materials have taken 25 years to make the transition from the laboratory to the shop floor; unfortunately, for a variety of factors, this time frame is still not
uncommon." Even if costs are significantly reduced, the general perception that ceramics are brittle, unpredictable, and fail catastrophically will remain. These limitations will not, however, deter ceramics manufacturers from trying to tap into the multi-billion dollar automotive industry.

2.5.1.4 Gas Turbines -

The other heat engine application where ceramic components promise to significantly improve performance is gas turbines. Because of the extremely high temperatures and enormous stresses in turbine engines, manufacturers and research agencies have invested considerable energy and funds into assessing the benefits of ceramic components for turbine engines. NASA, Ford, Westinghouse, Norton, Garrett, Pratt Whitney, Allison Turbine, and GE Turbine are some of the major players in developing components and total advanced ceramic gas turbine systems. Applications for these engines are passenger cars, commercial vehicles, military vehicles, civilian and military aircraft, and power generation.

It is largely agreed that ceramic turbine engines for passenger cars have the potential to reduce fuel consumption and increase the benefits of using low BTU fuels. However, manufacturing cost and difficulty fabricating quality components on a large scale persist in keeping ceramic automotive gas turbines in the testing phase. A study by the Automotive Consulting Group found that 19 of 27 (70%) engineers polled feel that if cost were no longer a factor, automotive ceramic gas turbines would become a reality. "There are many materials that are cheaper but not as good --- and there are other materials that are nearly as good but much more expensive --- ceramics hold the greatest potential for making (automotive) gas turbines a reality." Figure 2.5 shows a small 100 hp automotive gas

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The M1A1 main battle tank, for example, uses a 1500hp gas turbine. Turbines for passenger cars can be used for either primary power or in turboalternators for hybrid electric vehicles, where a small turbine is used to generate electricity.
turbine developed by Allison.

Civilian aircraft turbines are unlikely to incorporate load-bearing ceramic components in the near future. Professor Alan Epstein of MIT stated in a phone interview that it is highly unlikely that ceramic blades will be used in man-rated turbine engines. A more likely application, according to Epstein, would be components for small dispensable turbine engines, such as those found in stand-off missiles like the Tomahawk cruise missile. On the other hand, components under reduced mechanical stress such as nozzles and baffles could find their way into commercial aircraft engines because they offer increased erosion and corrosion resistance at high temperature, and are less likely to cause a catastrophic engine failure.

There seems to be guarded optimism on the near-term future of ceramics in turbine applications. However, reductions in processing cost, increased reliability and continued pressure to produce more environmentally friendly engines will bring an attendant rise in the number of structural ceramic components found in turbine engines.

The general belief is that the structural ceramics market will be the fastest growing, and the second most lucrative advanced ceramics market after electronics. Research in heat engine, biomedical, thermal, and wear applications for structural ceramics is, and will continue to be strong.

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Man-rated refers to the dependence of human life on the proper functioning of a component.
2.5.2 Electronic Ceramics -

According to Market Intelligence Research Corp., the total world revenue for ceramics in electronics is expected to more than double between 1991 and 1997, from $8.1 billion to 19.1 billion (compound growth of 5%). By 1995 the European market for electronic ceramics is expected to reach almost $2 billion, with Germany currently dominating at $531 million followed by France at $257 million (See Figure 2.6). The worldwide market for ceramic substrates (currently at $250 million) is expanding at 9%. Though alumina currently dominates market share, AlN is expected to replace alumina for certain applications and therefore will have high growth rates from 40% (Japan) to 60% (Europe).\(^\text{14}\)

![Figure 2.6](image)

A report by Business Communications Co. Inc.\(^\text{19}\) states that electronic applications constitute a mature market sector, with some segments exhibiting growth while others remain constant. However, new high temperature ceramic superconductors offer the potential for a very lucrative market in the future, according to the BCC study. Electronic ceramics could account for sales of almost $6.5 billion by 2000, a growth rate of 8.5% from $3.4 billion in 1992.
Daniel Shum of the American Consulate in Hong Kong has identified key technologies in an analysis of the Hong Kong electronics market. According to Shum, U.S. companies should focus on more sophisticated parts and components.\(^3\) The following are of special interest:

*Personal Computers and peripherals*

- ROM Chips
- PC chipsets
- inkjet print heads

*Telecommunications*

- telephone chips
- cellular telephone chipsets

*Industrial Electronics*

- 80x86 microprocessor chips
- power supplies
- sensors and transducers
- smart power devices

*Consumer electronics*

- complete and assembled watch movements
- specialty IC's for color televisions
- lenses, precision electronic motors, and noise suppression chips for VCRs and video cameras
- microcontrollers, sensors, solenoids and activators for air conditioners

Many of these applications would benefit from the use of advanced ceramic IC packaging. Arguably the most important application of ceramics in electronics, multilayer IC packages will make possible the high chip densities demanded for next generation electronic equipment.

Other key areas of the electronics market where advanced ceramics will be lucrative are:\(^{29}\)
- Sensors (gas)
- Thick film circuits
- Piezoelectric applications
- Electrooptic devices (shutters, displays, modulators, and image storage devices)
- Thermistors (temperature dependent resistors)
- Varistors (voltage dependent resistors)
- Ferrites (magnets)

2.5.2.1 Electronic Ceramics Market Conclusions

The market for advanced ceramics in electronic applications will be on the order of $20 billion by the year 2000. Companies developing new material systems, manufacturing processes, and applications based on next generation electro-ceramic components are assured a position in the largest advanced ceramics market. 3DP is capable of gaining a unique position in this segment if advanced, multilevel packaging can be fabricated.
2.6 Ceramic Forming Processes - Brief Overview

This section gives an overview of traditional ceramic forming methods, their limitations and strengths. It is intended to give a perspective on the advantages 3DP has in the area of advanced ceramics, and delineate where it has the most promise for success. Because these processes are based on differing physical phenomenon, or mechanical systems, each is limited to a segment of the total spectrum of ceramic products. The more traditional processes for the fabrication of ceramics components are:

- Dry Pressing
- Cold Isostatic Pressing
- Slip Casting
- Tape Casting
- Extrusion
- Injection Molding
- Green Machining

Some of the nontraditional processes are:

- Hot Pressing
- Hot Isostatic Pressing
- Other Rapid Prototyping Processes
- Molten Particle Deposition *
- Sol - Gel Process *
- Polymer Derived Ceramics *
- Vapor Deposition *
- Self Propagating, High Temperature Synthesis *
- Directed Metal Oxidation *
- Reaction Forming Processes *

Each of these processes is briefly described below with a more comprehensive section on rapid prototyping processes which have the potential to compete in the advanced ceramics market.

2.6.1 Dry Pressing

* Processes with an * are coating, particle creation, or other secondary processes and will not be considered in this report.
Dry pressing is the process by which ceramic powders are consolidated inside a cavity into a predetermined shape through the use of applied pressure acting in a uniaxial direction. Compaction forces are generally only applied in the vertical direction by counteracting mechanical or hydraulic rams.

**Characteristics:**

- Complex shapes with many holes, levels and diameters
- Production rates vary from 1 to 15 for large parts cutting wheels several hundred per minute for small simple parts (nozzles), up to several thousand per minute for small simple flat parts (i.e. cutting inserts)
- Low cost
- Good dimensional control

**Limitations:**

- As part complexity increases, dies become exceedingly expensive
- Excessive amounts of fine particles in mix can lead to particles becoming trapped between the punches and die wall, leading to increased frictional forces and die wear.
- Springback of the compressed part as the die retracts can lead to dimensional errors, fracture, or delamination of the part.

### 2.6.2 Hot Pressing

Hot pressing, or pressure sintering is a commonly used fabrication method that couples both thermal and mechanical energy to effect densification. Externally introduced shear and compression, the mechanical energy components, strongly influence the ceramic densification process. In general, the process is initiated by placing a powder mixture or a precompacted form into a pressing cavity and then sintering by applying an appropriate time-temperature-pressure profile. The superimposed uniaxial load provides the mechanical energy and is usually applied simultaneously with heat during processing. The resultant
increase in particle mobility and contact stress within the powder or preform rapidly accelerates the kinetics for densification. Calculations show that the densification rate can be increased by as much as twentyfold by the addition of mechanical energy during sintering.

*Characteristics:*

- Fully dense, fine-grained ceramic bodies
- Lower temperatures
- Excellent surface finish possible (due to small grain size)
- Shorter cycle times as compared with other sintering techniques
- Microstructure can be engineered with respect to grain size and pore size
- Bodies with large cross sections
- Can use materials not normally sinterable by other processes
- Can produce directional properties in some materials

*Limitations:*

- Costly equipment and tooling
- Limited tool and die life
- Limited shape capabilities (cylinders, disks)
- Only low aspect ratio parts possible

Products produced using Hot Pressing include optical windows, cutting inserts, tooling, ceramic armor, sputtering targets, heat engine components, nuclear reactor components, ceramic bearings, microwave absorbers, varistors and electro-optical components (resistors, blast goggles, magnets, recording heads).

2.6.3 Cool Isostatic Pressing

Isostatic pressing is a process to form ceramic components from a dry powder by uniform pressing from all directions. It is accomplished by enclosing the powder in a deformable mold and then collapsing that mold using a fluid medium to apply hydraulic pressure. This process takes place near room temperature.
Two forms of cold isostatic pressing exist, Wet Bag Isostatic Pressing and Dry Bag Isostatic pressing. WBIP uses an elastomeric bag filled with powder placed in a mold where pressure is applied hydrostatically. This method is popular because of its simplicity and low cost. DBIP uses two bags, one of which is an integral part of the press itself.

*Characteristics (Wet Bag):*

- Very few size or dimensional limitations, even for high aspect ratio parts
- Very uniform pressed compacts, leading to consistent densities and shrinkage yielding a reproducible process
- Moderate tooling costs
- No binder burnout required or drying times
- Attractive for high pressure applications

*Limitations:*

- Poor shape and dimensional control (difficult to achieve tolerances better than ±3% for wet bag pressing)
- Green machining before sintering nearly always required
- Only fairly simple shapes possible (cost directly proportional to complexity)
- Difficult to automate

*Dry Bag:*

- Very few size or dimensional limitations
- Uniform density (not as good as wet bag)
- High production rates (up to 60/min)
- Moderate tooling costs (somewhat higher than wet bag)
- Easily automated

*Limitations (Dry Bag):*

- Only simple shapes possible
- Poor shape and dimensional control (thin wall sections
can, however, be produced with dim. controls of about
± 0.05 mm (± 2 mils).

Cold Isostatic Pressing is used to produce a variety of products such as sparkplug insulators
(worldwide daily production on the order of 5 to 6 million), grinding balls, translucent
alumina tubes for sodium vapor lamps, refractory blocks and dinnerware.

2.6.4 Hot Isostatic Pressing

Hot isostatic pressing (HIP) has in many cases been found to provide unique
solutions for problems related to densification and the forming of ceramics. The process
utilizes uniform and omnidirectional pressure at elevated temperature to enhance
densification and interparticle bonding. An inert gas is used to transmit pressure. Because
no rigid tools are necessary to transmit pressure to the body, which enables high pressure
levels (15 to 50 ksi) to be used even above 3630° F.

**Characteristics:**

- Very powerful densification process due to high pressure
- Complex and well defined shapes
- Less and smaller voids
- Through use of encapsulation, ceramics can be densified at relatively low temps
- Grain growth and undesirable reactions can be controlled or avoided
- High uniformity of properties (i.e. density)
- Porous parts can be created

**Limitations:**

- Care must be taken in controlling interaction of processing gasses & part
- Great amount of Quality control necessary
• Removal of absorbed substances is a necessary step in processing
• Possible residual stresses in densified parts

2.6.5 Slip Casting

Slip Casting is an economical process that is widely used to produce complex shapes from a broad range of ceramic based materials. Applications are many, including artware, chinaware, sanitaryware, crucibles, filter media, structural tubing, bone implants and heat engine components.

A slip is a suspension of colloidal powders in an immiscible liquid (usually water). Slip casting entails pumping or pouring the slip into a permeable mold where capillary suction of the mold causes the liquid to be filtered from the suspending medium and a densely packed layer of particles to be deposited against the mold wall. Production rates can be increased by applying a pressure to the slip or by drawing a vacuum across the mold, both of which increase the flux through the mold.

 Characteristics:
• Large, complex parts possible
• Low mold and equipment costs

 Limitations:
• Low production rates
• Poor dimensional control

Particle surface chemistry is a dominant factor in the slip casting process because it regulates interparticle attraction and repulsion forces, which, in turn, have significant effects on slip rheology, casting rate, and microstructure evolution. The control of surface chemistry while preparing low-viscosity suspensions that are highly concentrated with powders is a major requirement of slip casting. Low viscosities (< 1 Pa s) and high solids concentrations (up to 60 % vol solids) are needed to maximize casting rate and green density. Regulating surface forces by altering the slip chemistry is also fundamental to eliminating cast layer heterogeneities such as large, isolated pores: size segregation of particles; and spatial variation of packing density.
2.6.6 Tape Casting

Tape casting is used to form large surface areas with very thin cross sections. These ceramic sheets are essentially two dimensional in nature and are used as the basic building blocks for many electronic substrates and packages. This process is normally based on nonaqueous liquid, because the drying process is evaporative in nature.

*Characteristics:*

- Ideal for the creation of very thin sheets
- High production rates for thin sheets (1 to 5 mils)
- Very precise thickness control of final tapes

*Limitations:*

- Limited to nearly 2-D shapes
- Requires secondary processes to create multilayer products

Tape casting has traditionally been used to make multilayered capacitors, and multilayer interconnection packages.

2.6.7 Extrusion

Extrusion is a ceramics processing method whereby a slurry is continuously forced through a die at high pressures. Ceramics that can be processed include silicon carbide, silicon nitride, and oxide materials. Shape capability has expanded from simple rods and tubes to complex profiles, sheets/films and honeycombs.

*Characteristics (extrusion):*

- Fabrication of constant cross sections that can be linearly formed
- High production rates

*Limitations:*

- Removal of binder and solvent complicated (during drying process)
- Warpage, and excessive shrinkage
• Parts may need to be fixtured during firing to maintain straightness, roundness and cope with large dimensional shrinkage. (applies to large or long parts)

• Expensive dies due to excessive wear when used with ceramics

• Post handling of extruded material problematic (can effect quality)

Extrusion, as with all ceramics forming processes, is very material sensitive, with utmost care necessary in their selection to achieve the desired product characteristics.

2.6.8 Injection Molding

Injection molding is a cyclic process in which a granular ceramic-binder mix is heated until softened, and then forced into a mold cavity, where it cools and resolidifies to produce a part of the desired shape.

Characteristics:

• High production rates possible

• Complex shapes w/ undercuts (raises die costs, however)

Limitations:

• Dimensional stability

• Reproducibility

• Skin formation - (due to restriction in the mold or excessive cavity pressure with either too low or too high cavity temperatures)

• Weld Lines

• Cracks become increasingly troublesome as the complexity of the part is increased (due to localized stress concentrations from uneven packing)

• Cost of dies and equipment

Ceramic products that have successfully been produced by injection molding include spark plugs, ceramic cores, thread guides, electronic parts, welding nozzles and dental braces. Despite these examples of successful applications, the market for injection molding
ceramics has remained both relatively small and fragmented. In recent years, injection molding has received special attention as a low-value ceramic parts at high volume, or high value at low volume ceramic parts process.

### 2.6.9 Green Machining

The operations classified as green machining are any of those that occur after the initial compaction of the ceramic body yet prior to full sintering. The strategy of green machining is to achieve fired parts as close to desired shape and tolerances as possible, thereby avoiding expensive grinding processes. Green machining is, however, a secondary process which does not directly compete with the above mentioned processes, and will therefore not be further discussed.

### 2.7 Rapid Prototyping

Rapid Prototyping (RP) has become an indispensable tool in a number of industries for designers striving to reduce product lead times and improve quality. With capabilities ranging from creating complex plastic visualization models to structural steel components directly from CAD models, RP has the ability to affect the design process at every stage.

Until the advent of novel additive forming processes, Numerically Controlled (NC) machining was the only automated "rapid prototyping" process available. NC machining, although capable of creating highly complex geometries with excellent surface finish and tolerances, is quite limited in terms of quickly producing components with internal features, and processing of very hard materials. Likewise, the costs of machining are prohibitive in the iterative design phase.

Beginning in 1987 with the first StereoLithography machines by 3D Systems, RP's promise of quickly and inexpensively transforming CAD data to physical components in a variety of materials has become reality. The initial application, as mentioned above, was to aid designers by turning drawings into models for evaluating concept, fit, form, function and marketing purposes. Markets have since emerged in low volume manufacturing, patterns
for replication processes, direct production of molds and dies, solid imaging of scientific, mathematical, and medical data, and artistic endeavours.\textsuperscript{38}

The image of RP for creating only nonstructural models persists but is giving way to the concept of \textit{Rapid Manufacturing (RM)}. RM connotes the concept of quickly going from CAD design directly to a finished component ready for use. An excellent example of this is the DSP process by Soligen (a 3DP spin-off), whereby metal casting molds are fabricated directly from CAD files which, after a light firing, can be cast. Soligen recently reported a turnaround time of less than one week from the time the CAD file was received, to receipt of the cast metal component by the client.

\textbf{2.7.1 Overview of Rapid Prototyping}

RP is broken into segments based on the materials used for forming a component and the method of creating geometry. Table 2.11 summarizes the RP industry along these lines, including traditional NC machining systems. It is interesting to note the relative costs of the different systems.

\textbf{2.7.1.1 Competitors to 3DP in Rapid Manufacturing-}

There are currently 6 commercial Rapid Prototyping systems marketed in the United States, with 4 others available only in their country of origin. Processes currently promising to compete with 3DP in direct fabrication of ceramic components are StereoLithography by 3D Systems, Laminated Object Manufacturing by Helisys, Inc., and Selective Laser Sintering by DTM, Inc.

\textbf{2.7.1.2 StereoLithography-}

StereoLithography has enjoyed the greatest commercial success in the growing rapid prototyping market, with its SLA-190, SLA-250, and SLA-500 systems defining the benchmark for the industry. Components are formed by selectively laser curing successive layers in a photocurable polymer vat. After the geometry for each layer has been defined by the laser, the component is lowered by a given amount (approximately 0.005\textquotedbl{}), exposing a
### Table 2.11 Commercially Available Fabricators

(See explanation of table, page 16.)

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Machine</th>
<th>Method</th>
<th>Materials</th>
<th>Envelope (in.)</th>
<th>Weight (oz)</th>
<th>Price (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subtractive</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Giddings &amp; Lewis</td>
<td>Planer-Type K &amp; C</td>
<td>Milling</td>
<td>All solid; (machinability desirable)</td>
<td>38,100</td>
<td>454,000</td>
<td>2,000-8,000</td>
</tr>
<tr>
<td>Boston Digital</td>
<td>BasaMat 5-axis</td>
<td>Milling</td>
<td></td>
<td>48-40</td>
<td>4,500-6,300</td>
<td>185-325</td>
</tr>
<tr>
<td>Kuka Machinery</td>
<td>DrillMill</td>
<td>Milling</td>
<td></td>
<td>16-25</td>
<td>2,200-6,300</td>
<td>66-114</td>
</tr>
<tr>
<td>Light Machinery</td>
<td>preLight</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>20</td>
<td>150-160</td>
<td>12-17</td>
</tr>
<tr>
<td>Okuma</td>
<td>TR Series</td>
<td>Milling</td>
<td></td>
<td>74,000</td>
<td>4,500-13,700</td>
<td>140-350</td>
</tr>
<tr>
<td>Enco Mader</td>
<td>Unimat PC</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>6</td>
<td>15</td>
<td>1.6</td>
</tr>
<tr>
<td>Sodick</td>
<td>A Series</td>
<td>Wire EDM</td>
<td>Electrical conductors</td>
<td>19-105</td>
<td>1,200-5,500</td>
<td>140-250</td>
</tr>
<tr>
<td><strong>Additive</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3D Systems</td>
<td>S1A</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>9-15</td>
<td>272-932</td>
<td>110-450</td>
</tr>
<tr>
<td>CMKT</td>
<td>S01CHP</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>64-255</td>
<td>850-1,200</td>
<td>900</td>
</tr>
<tr>
<td>Sony</td>
<td>FSC</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>23-450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EOS</td>
<td>Stereosan</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>18-144</td>
<td>800-1,300</td>
<td>500-1,000</td>
</tr>
<tr>
<td>Terri Num</td>
<td>S3tura</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>28-144</td>
<td>844-135</td>
<td>35-600</td>
</tr>
<tr>
<td>Cubital</td>
<td>Solda S000</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>18</td>
<td>4,500</td>
<td>550</td>
</tr>
<tr>
<td>DTM</td>
<td>Sinterstation 2000</td>
<td>Laser sintering</td>
<td>Thermoplastic polymers</td>
<td>25</td>
<td>2,000</td>
<td>280</td>
</tr>
<tr>
<td>Stratasys</td>
<td>3D Modelor</td>
<td>Laser cutting</td>
<td>Polyamides</td>
<td>25</td>
<td>140</td>
<td>172</td>
</tr>
<tr>
<td>Solmetal</td>
<td>DS3 System</td>
<td>Laser cutting</td>
<td>Powder adhesive</td>
<td>24</td>
<td>900</td>
<td>250</td>
</tr>
<tr>
<td><strong>Hybrid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helius</td>
<td>LDM</td>
<td>Stacking - laser cutting</td>
<td>Adhesive sheets</td>
<td>31-198</td>
<td>410-1,800</td>
<td>95-180</td>
</tr>
<tr>
<td>Salvadori</td>
<td>S4114</td>
<td>Shaping -</td>
<td>Adhesive sheets</td>
<td>625</td>
<td>1,800</td>
<td>1,800-2,000</td>
</tr>
<tr>
<td>Iowa Precision</td>
<td>Fabricator</td>
<td>Bonding -</td>
<td>sheets</td>
<td>645</td>
<td>23,000</td>
<td>430</td>
</tr>
</tbody>
</table>
new layer of polymer resin on the surface of the vat. This sequence is repeated until all layers of the component have been defined.

The primary application of StereoLithography is fabricating visualization models used in assessing a component's design. More recently, 3 D Systems made a software package called *QuickCast* available that gives SLA modelers the ability to make the equivalent of the wax pattern in investment casting. For a mere $10,000 (at the time of its introduction) owners of SLA machines can have the capability to create complex investment casting shells via SLA with no hardware or materials changes. Recent results reported in trade journals suggest that 3D Systems is also making progress in the area of direct fabrication of ceramic components by photocuring a resin loaded with a ceramic powder. Both of these advances, should they prove successful, pose a serious threat to Soligen's unique position in the casting industry.

2.7.1.3 Laminated Object Manufacturing-

Intriguing in that it makes wood from paper, LOM creates geometry by thermally binding sheets of Butcher paper together, and cutting the outline of a layer in the paper with a laser. All regions not part of the component are diced by the laser so that they can be removed once the component is finished. LOM is popular for modeling large complex components such as automobile headers, cylinder heads, etc. that are too large to model full scale with other systems.

As with StereoLithography, LOM is making inroads into the growing structural ceramics market. Following the process shown in Figure 2., the new CerLOM process substitutes ceramic tapes in place of Butcher Paper. According to an article in Material Technology July 1993, initial studies were conducted with non-structural glass-alumina compositions, reportedly having final material properties very close to those of alumina components formed by traditional processes. The next phase is to create structural components via the CerLOM process.
2.7.1.4 Selective Laser Sintering (SLS)-

SLS is perhaps the closest cousin of 3DP in the Rapid Prototyping extended family. As with 3DP, SLS selectively binds powder particles together to form individual layers of a 3D component. In the case of SLS, however, the binding is a thermal process where a laser "sinters" polycarbonate, nylon, or investment casting wax powders to form geometry. DTM's Selective Laser Sintering has promised structural ceramic capability for some time, but other than relatively simple components, full capability continues to elude SLS researchers.

2.7.1.5 Process Comparison-

Table ??? shows relative capabilities of the Rapid Prototyping processes discussed above.

**Table 2.12 Rapid Prototyping Processes Having or Promising Ceramics Capability**
(Source: Burton, Automated Fabrication, Prentice Hall; Englewood Cliffs, NJ; 1993)

<table>
<thead>
<tr>
<th>DSP</th>
<th>LOM-1015</th>
<th>SLA-250</th>
<th>SLS-Sinterstation 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>ceramic/metal/ paper/ceramic tape</td>
<td>photopolymer</td>
<td>polycarbonate, nylon, investment casting wax</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------------</td>
<td>--------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Accuracy (mm)</td>
<td>0.18</td>
<td>0.13</td>
<td>+-0.1mm</td>
</tr>
<tr>
<td>Envelope (cm)</td>
<td>40x40x40</td>
<td>25x25x25</td>
<td>30.5Dx38</td>
</tr>
<tr>
<td>Price</td>
<td>$250,000</td>
<td>$220,000</td>
<td>$289,000</td>
</tr>
</tbody>
</table>

2.7.1.6 Conclusions

Three Dimensional Printing remains the leader in rapid prototyping of structural ceramics and to a lesser extent metals, given its ability to accommodate practically any material obtainable in powder form. Unlike other RP processes, 3DP has already demonstrated the ability to create fully dense, high strength ceramic components which have very little overall shrinkage from printed to final part.
3 Market Analysis Methods

3.1 Introduction- Allowing Design Specifications to Lead the Way:

To reiterate, the primary focus of the 3DP Application survey, is to evaluate potential new applications of 3DP in the advanced ceramics market, identifying those that have the most economic promise in the near and long term. Given the size and diversity of the advanced ceramics industry, it is necessary to employ some form of data management to quickly make first order assessments of those applications which have promise for 3DP.

![Application Analysis Process Diagram](image)

Figure 3.1

Analysis software, described in detail in the next section, has been developed which performs the necessary data management for all applications considered, and performs a first order evaluation of their potential. The software acts as a filter, catching (but not discarding) those applications which are unsuitable for 3DP. In this case, the mesh of the filter are technical and economic parameters associated with an application. After a database of applications and their attributes has been compiled, the software automatically highlights those with the greatest potential.
In selecting the best manufacturing process for a given application, design teams must consider the required mechanical, thermal, chemical and production/cost related attributes dictated by the environment in which a product must perform. Take for example the simple connecting rod for automobile engines which can be manufactured by forging, sand casting, investment casting, permanent mold casting, powder metallurgy, and milling. Product attributes of a connecting rod include: specified geometry, high maximum compressive/tensile strength, excellent fatigue characteristics (hundreds of millions of cycles over the life of the engine), high corrosion resistance, high fracture toughness, and low cost at high production volumes. Using these specifications as a guideline, a design team eliminates those manufacturing processes which are incapable of fabricating the part. In many instances the design team will be able to quickly eliminate several processes based on experience and common sense. There are, however, products for which the process of choice will vary greatly with production volume, (i.e., connecting rod). For such products it is necessary to carry out a systematic evaluation of competing processes, comparing their strengths and limitations. Figure 3.2 shows the progression of sequentially filtering candidate processes based on the required product specifications, until the optimal product-process pairing is determined.
In the case of the 3DP application survey, engineering characteristics of the 3DP process are compared with the product attributes of a variety of candidate applications. These applications are then ranked by how well suited 3DP is to their manufacture. The details of how this selection process is performed are outlined in the following sections.

3.2 Software Analysis of new Applications For 3DP- Overview:

This section outlines the development of software tools to aid in analyzing the advanced ceramics market. A brief history is presented on the software's evolution from automated House of Quality and Pugh chart metaphors, to the current system based on the Quality Loss function. Following this is a detailed description of how the Quality Loss function is applied to 3DP, results of using the software for analyzing candidate applications, and concluding comments.

3.2.1 Initial Efforts

Evaluation of new 3DP applications was initially carried out by an application "filter". Basic information such as have internal geometry?, small enough for printer?, require multiple materials?, low production volume?, etc. was entered in a binary fashion for each application. Those applications passing through the "meshes" were set aside for further consideration. This was a very quick method of screening applications for the current 3DP system, but had no capacity to highlight which aspect of the 3DP process require improvement to increase its market share. Adding this functionality, the 3DP application filter evolved into spreadsheet and database versions of the House of Quality and Pugh Charts.

Simply, the house of quality is a graphical method for translating customer desires into measurable engineering characteristics of a product. Often overlooked, this translation helps a design team can concentrate on those product attributes which have the greatest effect on the customer's perception of the product. Pugh charts are used to compare
competing design concepts by analyzing them relative to each other based on design criteria. After several iterations, the best concept is filtered to the top of the group of candidates. On the following pages are examples of an early House of Quality spreadsheet and Pugh Process Selection Matrix.

*House of Quality (HoQ)* - Engineering characteristics are based on the process being evaluated, and represent those parameters which can be influenced to meet the needs of the customer. The HoQ matrix is used to show the degree of correlation between the engineering characteristic and the customer attribute. The higher the number, the more directly that engineering characteristic is able to satisfy a specific desire of the customer.

Deciding upon the column headings is once again a matter of choosing an acceptable degree of abstraction, but should be much more detailed than the customer attributes. For example, the customer says that complex geometry is crucial for this product, referring to the chart it is seen that *layer thickness*, *droplet placement accuracy*, and *control software* all play a part in meeting this need.

Once the HoQ has been used to locate the general engineering characteristics of the system which have the greatest influence on creating satisfying components, these areas can then be further broken down in more detail and reanalyzed. For example, should it be found that *droplet placement accuracy* has a great influence on overall system performance, it would then be broken into its basic components (ballistics, flow rate, etc.) and reevaluated.

*Pugh Process Selection Matrix* - Just as when used for design selection, the Pugh selection matrix allows a direct comparison of the various ceramics processing methods' applicability to manufacturing a given product (see example below). When considering anything but a novel product, the comparison can be limited to a "head to head" comparison between the method industry has embraced, presumably because it is the most economical, and 3DP. For a completely new product, the 3DP filter can be used to help narrow the field of processes which should be analyzed by the Pugh matrix, thus saving work. By "running"
the matrix with 3DP as the *datum* it can quickly be seen how 3DP stacks up with the competition, and in which areas it falls short. An example of a Pugh chart is on the following page.

Notice that the last row of the chart is titled *KILL SWITCH*. This feature allows the user to enter a hugely negative number for any of the processes, thereby assuring it cannot return a positive final value. This is to eliminate processes which are obviously unable to produce a given part, but possess other positive qualities giving it a favorable end value. For example, tape casting is able to give tight dimensional tolerances, good surface quality, high production rate and low costs, which together outweigh the fact that it cannot make complex 3D parts. Running the chart for an engine block would erroneously give a fairly favorable value for tape casting, obviously not the right decision.

These methods were, however, eventually merged and improved to form the current application analysis software. More than any other, the reason for abandoning the HoQ and Pugh analysis processes as they were was to reduce the number of subjective components to the analysis. As opposed to "good, same, worse" analysis, hard engineering parameters are compared such as \(R_s\) surface roughness, and four point bending strength. Although simple and intuitive, the House of Quality and Pugh analysis methods were not ideally suited for the purposes of the 3DP application survey.

### 3.3 Introduction to Quality Loss and Economic Analysis Methods

This section defines and gives examples for the use of the Quality Loss function as it is applied to the 3DP application survey.

Ability of a given process to fabricate a particular component to the desired specifications is determined using the quadratic Quality Loss Function. Quality loss in this context means the deviation of the actual component from the specified "ideal" component. This method differs conceptually from Pugh charts' "better, same, worse" qualitative analysis, in that it is a *quantitative* calculation of deviation from the optimum. Not only does this method show in which areas a concept is weak or strong, but also gives an
## House of Quality for Turbine Blades and 3DP

<table>
<thead>
<tr>
<th>Layer</th>
<th>Size Range</th>
<th>Geom 1-2</th>
<th>Geom 3-5</th>
<th>Variable</th>
<th>Material</th>
<th>Surface</th>
<th>Features</th>
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<th>Texture</th>
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<th>Accuracy</th>
<th>High Surface</th>
<th>Quality</th>
<th>High MTBF</th>
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</tbody>
</table>

### Notes
- **Importance** table reflects the importance of each attribute.
- **Customer Attributes** include造价 Cost, Production Rate, Part Mix, Equipment Cost, Tooling Cost, High MTBF, Unattended Operation, and User Friendly.
- **Engineering Characteristics** include Size Range, Geom 1-2, Geom 3-5, Variable, Material, Surface, Features, Controlled, Texture, Dimensional Accuracy, High Surface Quality, High MTBF, Unattended Operation, and User Friendly.
- The values in the table represent the importance level, with 1 being the lowest and 9 being the highest.
### Pugh Process Selection Matrix

<table>
<thead>
<tr>
<th>Engineering Chars.</th>
<th>Relative Importance</th>
<th>Compr:</th>
<th>Dry Pressing</th>
<th>CIP</th>
<th>HIP</th>
<th>Tape Casting</th>
<th>Slip Casting</th>
<th>Extrusion</th>
<th>Injection Molding</th>
<th>Hot Pressing</th>
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<th>3DP</th>
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</table>

**Relative Value**
-5 -9 -9 -6 -9 -5 -6 -2 -1 0

**Weighted Value: based on importance**
-10 -27 -27 -20 -29 -25 -16 -10 -1 0
indication of how deviations from the desired specification affect the overall quality of the
product. Details of the Quality Loss Function are handled in greater detail the next section.

3.3.1 Quality Loss Function

The concept of "quality loss" is that if a given engineering parameter deviates from
its nominal design value, then there is some degradation, or loss of performance. Once a
parameter has strayed from the target value by some threshold amount, the performance has
degraded to the point where the product or process is no longer acceptable. Analyzing
where the quality losses occur in manufacturing will lead to process improvements, lower
costs and increased customer satisfaction.

M. Phadke, developer of the Quality Loss methodology based on the work of
Taguchi and others, illustrates the usefulness of the quality loss concept. Phadke writes:

It is common to measure quality in terms of the fraction of the total number of
units that are defective. This is referred to as fraction defective. Although
commonly used, this measure of quality is often incomplete and misleading. It
implies that all products that meet the specifications (allowable deviations from the
target response) are equally good, while those outside the specifications are bad.
The fallacy here is that the product that barely meets the specifications is, from the
customer's point of view, as good or as bad as the product that is barely outside the
specifications. In reality, the product whose response is exactly on target gives the
best performance. As the product's response deviates from the target, the quality
becomes progressively worse.

**Example - Television Set Color Density:** The deficiency of fraction defective as a
quality measure is well-illustrated by the Sony television customer preference study
published by the Japanese newspaper, *The Asahi*. In the late 1970s, American
consumers showed a preference for the television sets made by Sony-Japan over
those made by Sony-USA. The reason cited in the study was quality. Both
factories, however, made televisions using identical designs and tolerances. What
could then account for the perceived difference in quality?

In its investigative report, the newspaper showed the distribution of color density
for the sets made by the two factories (see Figure 3.3). In the figure, $m$ is the target
color density and $m \pm 5$ are the tolerance limits. The distribution for the Sony-Japan
factory was approximately normal with mean on target and a standard deviation of
$5/3$. The distribution for Sony-USA was approximately uniform in the range of $m \pm 5$.
Among the sets shipped by Sony-Japan, about 0.3 percent were outside the tolerance
limits, while Sony-USA shipped virtually no sets outside the tolerance limits. Thus
the difference in customer preference could not be explained in terms of the fraction

61
of defective sets. The perceived difference in quality becomes clear when we look closely at the sets that made the tolerance limits. Sets with color density very near \( m \) perform best and can be classified grade A. As the color density deviates from \( m \), the performance becomes progressively worse, as indicated in Figure 3.3 by grades B and C. It is clear that Sony-Japan produced many more grade A sets and many fewer grade C sets when compared to Sony-USA. Thus, the average grade of sets produced by Sony-Japan was better.

![Figure 3.3]

In short, the difference in the customer's perception of quality was a result of Sony-USA paying attention only to \textit{meeting the tolerances}, whereas in Sony-Japan the attention was focused on \textit{meeting the target}.

It was decided to adapt the concept of Quality Loss to the 3DP Application analysis software because it allows a rigorous comparison between the specifications of a given product and the capabilities of 3DP. More importantly, Phadke's method allows the software to highlight those engineering characteristics of 3DP which lower the overall quality, making apparent where more activity is necessary.

### 3.3.2 Quality Loss Calculations

Quality Loss as proposed by Phadke is calculated by a quadratic function which increases as the square of the deviation from the ideal parameter. There are three primary variations of the loss function: \textit{Nominal is Best}, \textit{Bigger is Better}, and \textit{Smaller is Better} (see
Figure 3.4). Nominal is best calculates the loss for any positive or negative deviation from a nominal target specification. Bigger is Better gives increased loss for deviations less than the target value, e.g., bond strength - the larger the better but below target is unacceptable. Smaller is Better is the opposite of Bigger is Better, e.g., reject rate - ideally there would be 0 rejects.

Process parameters are used as the x value in the Quality Loss calculations. Product parameters are the m values in the Quality Loss calculations.

For an example of a Bigger is Better process parameter, consider the following: If green strength were specified to be 1.8 MPa and the process could deliver only 1.45 MPa, the quality loss would be calculated in the following manner:

\[
Loss = \frac{(\text{Target Green Strength})^2}{(\text{Process Green Strength})^2}
\]
\[ \text{Loss} = \frac{(1.8)^2}{(1.45)^2} = 1.54 \]

A loss of 1.54 indicates that the process was unable to meet the desired target (a loss of 1.00 is indicates within tolerance), and because 1.54 is a poor score, this characteristic of the equipment is in need of improvement. If, on the other hand, the process were capable of creating 2.5 MPa green components, the loss would be reduced to 0.52.

Reject rate is an example of a Smaller is Better type characteristic. Given that a certain piece of equipment had a reject rate of 100 parts per 10,000 and the company were striving for 20 per 10,000, the loss would be \( \frac{100^2}{20^2} = 25 \) (this is a completely unacceptable value!). Whereas equipment with a reject rate of only 18 per 10,000 would represent a loss of only 0.81 for the company.

### 3.3.3 Adaptation of Phadke’s Quality Loss Function

The bigger is better and smaller is better calculations suggested by Phadke have limitations, however, which must be addressed. Firstly, these functions do not take into account the range of deviation normal for a given parameter. This distinction of the target being only a portion of the absolute scale for a given parameter is very important.

Figure 3.5 tries to illustrate the point: the tree and the building are the same distance from where the plane starts the takeoff roll. If the plane has enough power to climb to 50' by the end of the runway there is no problem. But for every horsepower less than this critical value, the plane begins to have troubles. The tree is an example of loose tolerance around the target (i.e. 50' altitude at 1750' of runway), because the twigs progressively become stiffer until they are large enough to damage the plane. The building, on the other hand, is an example of tight tolerances around the bigger is better target. If the plane generates just a few less horsepower, it will be destroyed by the building. The moral is that it is important to look a the relative value of a parameter around a bigger is better or smaller
is better target instead of the absolute scale.

![Figure 3.5](image)

For a less lethal example, if the customer specified surface roughness for a component smoother than 9 μm Rₐ but 3DP can only produce 9.5 μm Rₐ the loss by Phadke's method is \((9.5/9)^2 = 1.11\). But if the range of values that makes sense for this parameter is 9.0 ±0.1, then the loss for a roughness of 9.5 becomes \((0.5/0.1)^2 = 25\).

Taking these factors into account, the new quality loss for bigger is better is

\[
\text{if (actual value } \geq \text{ target value) then}
\]

\[
\text{Loss} = \left(\frac{\text{target value}}{\text{actual value}}\right)^2
\]

\[
\text{else}
\]

\[
\text{Loss} = 1+\left(\frac{\text{target - actual}}{\text{range}}\right)^2
\]

where range is the set of acceptable values around the target (tolerances). Similarly, the corrected equation for smaller is better type product attributes is:

\[
\text{if (actual value } \leq \text{ target value) then}
\]

\[
\text{Loss} = \left(\frac{\text{target value}}{\text{actual value}}\right)^2
\]

\[
\text{else}
\]

\[
\text{Loss} = 1+\left(\frac{\text{target - actual}}{\text{range}}\right)^2
\]

An example of how the smaller is better function works, Figure 3.6 shows Loss curves for a product attribute with target value = 16 and tolerance ranges of 2, 3, 4, and 5. The steepest curve represents a target window of 2, the flattest curve is that for a relatively
large window of 5. All values under the target of 16 go to zero with the square of the value (actual/target).

To reiterate, the necessity for this variation on Phadke's equations is to emphasize the range of values around the target, not the absolute scale.

**Smaller Is Better Quality Loss for different ranges about the target**

*Figure 3.6*

3.3.4 Weighted Quality Loss

Customer involvement in the design and production planning phases of a project helps to assure that a winning product will result. Weighting the quality loss function is one method whereby the customer can indicate the importance of various process/product parameters. Weightings of 1 - 9 (1 = not important, 9 = Very important) are entered by the user. This allows the process selection process to be fine-tuned to the needs of the
individual customer, taking into account driving factors not represented by the raw technical specifications of the desired product.

As shown on pages 62 and 63, weightings for each category are entered on the right of the Quality Loss matrix. Weights are in turn multiplied by the loss values in each of their respective rows and summed to give a weighted loss value. Comparison of the weighted loss values for the various manufacturing processes gives an excellent overall indication of which process is best suited to meeting both technical and economic goals for the desired component.

### 3.3.5 Economic Calculations

"There have been countless machines designed to perform tasks in a technically elegant manner. However, only those machines that can operate in a cost-effective manner will become commercial successes."² The economic calculations performed by the analysis spreadsheet are designed to give the user insight into the roles played by major cost drivers such as operator wages, material costs, postprocessing costs, production volume, financing rates, and tax rates. Bottom line for this analysis is the present worth of a capital investment for manufacturing equipment. In simplified terms, the purchasing engineer must be able to convince management that investing in equipment to produce a given product will achieve profit goals. Naturally the present worth of the total capital investment must be positive and as large as possible. Calculation of present worth is as follows (from Slocum):

1. \( CF_o \) (Initial Cash Flow) = (new machine cost) + (operator training cost) + (spare parts cost)
2. \( CF_i = CF_i = CF_{n+1} = \text{number of products per year} \times \text{profit per product} \)
3. \( CF_e = \text{number of products per year} \times \text{profit per product} + \text{salvage value} \)
4. \( PW_{12} \) (present worth @ 12% ROI) = \( CF_o + CF_{i+2} \) \((P/A, 12\%, n-1) + CF_i \) \((P/F, 12\%, n) \)

Where \((P/A, i, n-1) = ((1+i)^{n-1}-1)/(1+i)^{n-1}\)

\((P/F, i, n) = 1/(1+i)^n\)
Federal tax laws, however, can have a considerable effect on the present worth of an investment. Therefore, recovery period and investment tax credit are also incorporated into the present worth calculations to give a more accurate picture of how "smart" the capital investment would be.

Investment tax credit on domestic equipment was 10% in 1987, which is essentially a 10% rebate of the purchase price of the equipment\(^2\). Capital recovery allows a company to write off the cost of the equipment over the recovery period, reducing taxable income by an amount equal to \((\text{purchase price-tax credit})/\text{recovery period}\) per year. The modified present worth calculation is as shown on the following page.

1. \(\text{CF}_0\) (Initial Cash Flow) = (new machine cost) + (operator training cost) + (spare parts cost)
2. \(\text{CF}_1 = \text{CF}_2 = \text{CF}_{n-1} = \text{number of products per year} \times \text{profit per product} + (\text{new machine cost-rebate})/\text{recovery period}\)
3. \(\text{CF}_n = \text{number of products per year} \times \text{profit per product} + \text{salvage value} + (\text{new machine cost-rebate})/\text{recovery period}\)
4. \(\text{PW}_{12}\) (present worth @ 12% ROI) = \(\text{CF}_0 + \text{CF}_{1:2} (\text{P/A, 12\%, n-1}) + \text{CF}_1 (\text{P/F, 12\%, n})\)

\[
\text{Where } (\text{P/A, i, n-1}) = ((1+i)^{n-1}-1)/(i(1+i)^{n-1} \text{ and } (\text{P/F, i, n}) = 1/(1+i)^n
\]

Tax laws favor more expensive equipment to a certain extent because both the rebate and right-off are increased as equipment costs go up. There is, however, an optimal equipment cost for each situation at which the tax laws offer the greatest advantage. The spreadsheet developed for this analysis greatly increases the user's ability to manage such counterintuitive trends.

### 3.3.6-Implementation of Methodology

Spreadsheet and database software allow the user to exploit the Quality Loss concept as an analysis and optimization tool for large amounts of process and product data. Developed and tested in Excel, the methodology has evolved to its current state described in this paper. "What if" scenarios are possible by automatically varying selected parameters.
and logging their effect on crucial output such as net present value and quality loss. This is extremely useful in analyzing trends and the complex interaction of the variables.

Database implementation is less flexible but allows a greater number of products and processes to be analyzed once the system is properly "tuned". It is envisioned that the two systems will work in concert, the database being a first cut analysis tool and the spreadsheet being a more precise, detailed device for looking at trends and the interplay of different process/product parameters. Further details of the database are discussed in section ????.

**What this methodology can do:**

- Give an accurate suggestion for product/process pairing based on technological and economic considerations
- Be a useful tool for convincing potential customers or management that an equipment purchasing decision meets profit goals by showing hard numbers
- Give users the ability to quickly analyze the complex interaction of the many variables which comprise such projects, allowing optimization for profit and customer satisfaction
- Be expanded to consider any number or type of processes with as little or much resolution on process and product parameters as necessary to achieve the desired accuracy of selection

**What this methodology cannot do:**

- Suggest new applications - this is the task of the user's creative talents
- Guarantee the quality of input parameters - "Garbage in garbage equals garbage out". For this reason users must carefully research process parameters for their particular manufacturing conditions.

Views of the Quality Loss and Economic analysis spreadsheets developed in Excel are shown on the following pages. The user inputs product attributes, engineering characteristics, and customer weights into the proper cells and Quality Loss, print time, and economic forecasts are automatically calculated.
3.4 Interactive Analysis Database

Wading through the multitude of applications which are a possible match for 3DP solution is a daunting task considering the size and diversity of the advance ceramics market. For this reason a database storing information on each of the candidate applications has been created to match product attributes with the capabilities of 3DP. Software-based process consultants present an efficient way of managing and categorizing a large number of applications and processes.

3DP, as do all manufacturing processes, has limitations which define the range of components it can produce. Simply, the database compares the engineering characteristics of 3DP with the attributes of the application (surface quality, strength, size, etc.). It not only highlights which product attributes 3DP can or cannot achieve (within tolerance), but also calculates how far 3DP is from the target.

3.4.1 Architecture of a Database System

The process selection database can be dissected into three major segments: Product Attributes (PA), Engineering Characteristics (EC) of the manufacturing process, and Analysis. Figure 3.7 depicts the general layout of a selection database.

![Figure 3.7: Schematic of Database System](image)

3.4.1.1 Product Attributes

PA's are entered under the broad categories geometry, material, and production. From this information the database searches through the available information on the
production equipment's engineering characteristics and suggests the best product-process combination. Specific examples of product attributes would be $R_s$, surface roughness, green density, ultimate tensile strength, etc. There are no limits, however, to the number and detail of these parameters. It must be emphasized that selection of process and product parameters is critical to the value of this analysis and should be done with care.

3.4.1.2 Engineering Characteristics:

Engineering Characteristics define the manufacturing process for the database. Limitations and strengths are cataloged in either relative or absolute terms. For example, absolute EC's for Electrical Discharge Machining (EDM) include: workpiece conductivity > $x \text{ Ohm}^{-1}$, production rate < $y \text{ cm}^3$/hr, geometry limited to complex shaped holes and pockets, and surface roughness > $z \text{ RMS}$. Figure 3.8 shows an abstraction tree for breaking down the production process into fundamental elements from general characteristics.

**FIGURE 3.8: Engineering Characteristic Levels of Abstraction**

[Diagram of abstraction tree showing Can this process make the part? with branches for Mechanical, Economic, Thermal, Electrical, Chemical, Geometry, Production, Material, Size, Geom. Category, Variable Material, Surface Features, Dimensional Accuracy, Surface Quality]
3.5 Use and Functionality of the Quality Loss Database and Spreadsheet

This section covers how the user interfaces with the 3DP Application software to perform the Quality Loss analysis, as well as how they manage the user's input to determine a loss score for each application. Images of how the database and spreadsheet are displayed to the user are included here to illustrate the "user friendliness" of the interface and, hopefully, to convey the commercial potential of the software.

3.5.1 Entering and Reviewing Data

This section offers a brief description of data input fields through which the user enters and accesses the information stored in the database. A more thorough description of each field and associated mathematical functions appears in Appendix B.

Data entry follows the sequence shown in figure 3.8. The user is greeted with the screen shown on the following page which has "fields" ,or data entry blanks, for an application's various organizational data such as name, description, date entered, etc. If available, a digitized image can also be included. Several buttons appear in control panels on the right half of the display. Here the chooses from several "rooms" for entering general data on the application (size, surface roughness, etc.), material selection, economic parameters, review 3DP's capabilities (or change them for "what if?" scenarios), select the geometry category (described later), surface roughness, or look at administrative sections such as a list of all applications. Switching to another room is as simple as selecting one of the buttons with a mouse.

![Data Entry Sequence Diagram](image)

Figure 3.9
Compact core cross flow heat exchanger for waste heat recovery (1600 °C glass/steel/aluminum furnace) applications.
### Product Information

**Product:** heat exchanger core  
**Product ID:** 153

<table>
<thead>
<tr>
<th>Product Attributes</th>
<th>Target</th>
<th>Tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions: x</td>
<td>30.5 cm</td>
<td>+ 0.01 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 0 cm</td>
</tr>
<tr>
<td>y</td>
<td>30.5 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>z</td>
<td>20.32 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometry Category:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Surface Roughness:</td>
<td>1200 µm Ra</td>
<td>+ 0 µm</td>
</tr>
<tr>
<td>Tolerance:</td>
<td>0 µm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOR:</td>
<td>25 MPa</td>
<td>- 2.5 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density:</td>
<td>100 vol %</td>
<td>+ 2.5 vol %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary Material:</td>
<td>0 vol %</td>
<td>+ 0 vol %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent void volume:</td>
<td>60 vol %</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production Volume:</td>
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<td>+ 10 units/yr</td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product Value to</td>
<td>1.51 $/s</td>
<td></td>
</tr>
<tr>
<td>Production Cost Ratio:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product Selling Price:</td>
<td>2690 $</td>
<td></td>
</tr>
</tbody>
</table>

**Diagram:**

- **Product**
  - Main Screen
  - 3DP
- **Process**
  - Geometry
  - Economics
  - Material
  - Analysis

*Surface roughness estimates taken from Kalpakjian pp. 378 & 816*
Geometry Category Selection Field

**Product Name:**
Heat Exchanger Core

- Simple 2D
- Simple 3D
- Compound Curves, Simple Internal
- Compound Curves, Simple Internal, Undercuts
- Compound Curves, Complex Internal, Undercuts

More! (use scroll bars)

Additional Geometric Constraints

1. Internal Undercuts: 

2. Non Uniform Cross Sections:

3. Closed internal Cavities:

---

75
<table>
<thead>
<tr>
<th>Process Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Product Dev</td>
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<tr>
<td></td>
<td>5</td>
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<tr>
<td></td>
<td>25.6</td>
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<td>20</td>
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<td></td>
<td>200</td>
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<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>200000</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.0177</td>
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</table>

<table>
<thead>
<tr>
<th>Tool Speed (rpm)</th>
<th>Cutted Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>30.5</td>
</tr>
<tr>
<td>0.32</td>
<td>15.24</td>
</tr>
<tr>
<td>45</td>
<td>30.5</td>
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</tbody>
</table>

DONE
## Economic Considerations

<table>
<thead>
<tr>
<th>Product</th>
<th>heat exchanger core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator Wages ($/hr)</td>
<td>25</td>
</tr>
<tr>
<td>Annual Overhaul Costs ($)</td>
<td>2000</td>
</tr>
<tr>
<td>% direct operator supervision</td>
<td>25</td>
</tr>
<tr>
<td>Routine Overhaul Costs ($)</td>
<td>2000</td>
</tr>
<tr>
<td>Hours per Year</td>
<td>2000</td>
</tr>
<tr>
<td>Routine Overhaul Frequency (hr)</td>
<td>200</td>
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<tr>
<td>Powder Cost ($/kg)</td>
<td>145</td>
</tr>
<tr>
<td>Component Weight (g)</td>
<td>25,027</td>
</tr>
<tr>
<td>Production (units/hr)</td>
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<tr>
<td>Production (units/yr)</td>
<td>110</td>
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<td>Product Value ($)</td>
<td>2690</td>
</tr>
<tr>
<td>Additional Cost per product ($)</td>
<td>500</td>
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<tr>
<td>Machine Cost ($)</td>
<td>200000</td>
</tr>
<tr>
<td>Die Cost ($)</td>
<td>0</td>
</tr>
<tr>
<td>Operator Training ($)</td>
<td>3000</td>
</tr>
<tr>
<td>Spare Parts ($)</td>
<td>1500</td>
</tr>
<tr>
<td>Salvage Value</td>
<td>60000</td>
</tr>
</tbody>
</table>

| Depreciation | DEPREC 10 |
| Tax rate | TAXRATE 43 |
| Lending Rate | LENDRATE 12 |
| Years of term | LENDYEAR 3 |

Cost per Part
$ 1,750

Present Worth of Investment
$ 148,000
Product Information Room-

Information on the size, geometry, surface quality, four point bend strength, density, percent secondary material (i.e., selectively doped areas), void volume, product value to production cost ratio, and selling price are all entered here. Next to each attribute are tolerance fields, which, depending on the values input into them, indicate to the database if the attribute is a nominal is best, bigger is better, or smaller is better.

For the database to calculate a bigger is better type parameter, a zero is entered in the + field in the tolerance column (this is contrary to the normal tolerance nomenclature where a + 0 tolerance would indicate a dimension is to be no larger than the target). The - value sets the steepness of the loss curve as described in the previous section. For example, surface roughness is a bigger is better type parameter (i.e., the rougher a product's surface is to be, the able 3DP is to match this need). Therefore a zero is entered in the + field and a value to set the steepness of the curve is entered in the - field. Smaller is better functions in reverse of bigger is better, and nominal is best functions just as outlined by Phadke, using the + and - tolerances to set the d parameter (refer back to section 3.3).

The Product Information "room" prompts the user for basic product attributes. Some fields are automatically filled based on the input to others (rationale for this is discussed in Results section of this chapter). x,y, and z dimensions refer to the smallest rectangular volume which can encapsulate the component. From this the number of layers in the component, as well as the number of components that can be packed into a single piston are calculated.

Pressing the Geometry button switches to the Geometry Category Selection Field where a representative shape is selected from one of five basic categories, beginning with simple 2D geometry and going to complex geometry with internal cavities. Limiting the user to these five geometric categories greatly reduces the effort needed to describe a component to the database\(^\dagger\). A more advanced version of this software would read STL files of a component and assign complexity, size, weight, etc. data automatically.

\(^\dagger\) Initially this field was used to distinguish which components could be made by which processes based on geometric complexity. The ability to do head to head comparisons of competing processes has been removed from the latest version of the database software but is still possible with the spreadsheet version.
Pressing the *Material* button switches the view to the Material Information room where a material database is accessed. The user simply selects one of the materials entered in the database pulldown menu and all values for characteristics such as MOR, thermal conductivity, and density are automatically filled in the appropriate fields.

Likewise, pressing the *Surface Roughness* button switches to the surface roughness screen where the user can select the process by which the given application is currently made. A typical $R_s$ surface roughness for the selected process is called from the database and entered where appropriate. Roughness values in the database are taken from Kalpakjian's *Manufacturing Engineering and Technology*. Justification for this approach is given in the results section.

*Secondary Material* accounts for those applications needing to make use of 3DP's ability to create functionally gradient materials. *Percent Void Volume* indicates the percentage of the rectangular volume (entered in the dimension fields) which is un-printed. Knowing the volume of the printed part is important for calculating its weight and subsequently its materials cost. *Product Value to Production Cost Ratio* indicates profit margin expected on an application. *Selling Price* is the market value of a component in either green form or as a finished product.

**Economic Considerations**

In the *Economic Considerations* room, parameters affecting the cost of producing a given component via 3DP are automatically entered by the database to preset values. Fields pertaining to the specific application are either automatically calculated from data entered in the General Information room or are entered here. Post processing costs, for example, can be entered to get the total 3DP manufacturing cost / unit estimate. The preset values can be changed to represent process enhancements, and play "what if" scenarios.

The user is able to review and alter 3DP process parameters in the *3DP* room. Basic process capabilities are included covering build rate, maximum component size, accuracy, and current materials limitations (discussed in the chapter on materials). These fields define the engineering characteristics used in the Quality Loss calculations.
Once all product attributes have been entered and any 3DP engineering characteristics have been changed from their default values, the *Product Analysis* room is able to display information on quality loss and unit manufacturing costs for both a prototype and full production at maximum printer capacity. To compare the current application with others for which the necessary information has been entered, the *product list* button is depressed, showing a list of applications sorted by ascending quality loss score.

### 3.6 Assumptions Made for Application Analysis

Assumptions are necessary to reduce the overall complexity of the analysis and to add uniformity to the comparison. These assumptions are outlined here and their impact on the application survey are discussed.

#### 3.6.1 3DP Characteristics

Currently there are two fronts in the advancements of the 3DP technology, Soligen's DSP system and the Alpha 3DP Printer at MIT. These machines differ primarily in resolution, buildrate, piston volume, and cost. For the sake of this study, all 3DP related parameters are those of the MIT Alpha machine. To simulate the engineering characteristics of the Soligen DSP system, fields in the 3DP room need merely be changed to those of Soligen's machine.

#### 3.6.2 Application Attributes

This section covers assumptions made regarding the attributes of applications in the database. Specifically, problems associated with large families of related components, and less than complete data are discussed.

Application attributes were gathered from the literature, interviews, and, where sufficient information was not available, inferred based on knowledge of current manufacturing processes. With the initial 3DP application filter methods, detailed information was not necessary to make assessments of which applications were or were not
suitable for 3DP. With the development of the Quality Loss database, which compares numeric attributes with their engineering characteristic counterparts, substantially more information is necessary. Even with less detailed information, however, Quality Loss is still capable of making first order suggestions as to which applications are promising with 3DP, but its resolution is limited. Ideally the survey would include very specific information on each application directly from the manufacturer.

The initial review of the advanced ceramics market yielded numerous families of applications with general information relating to each family. For example: ceramic turbine blades. Turbine blades exist in a great variety, with different types in each engine, different geometries from engine model to engine model, and from manufacturer to manufacturer. Therefore a representative component was selected and entered in the database (in this case an actual turbine blade was measured).

Incomplete and conflicting data is the largest detractor to the Quality Loss function's ability to perform as designed. If more accurate data is not available, the database infers information on surface roughness, manufacturing tolerances, and strength from knowledge of the current manufacturing process and material. This is by no means an optimal solution, but it preserves the original intent of the 3DP Application Survey by providing enough information to make a rough estimate of 3DP's suitability. If there is no information on either manufacturing process or material, the candidate cannot be processed and is discarded.

Manufacturing process surface roughness and tolerances are taken from Kalpakjian. Material characteristics are compiled from Coors Ceramics current product offering (with the exception of their aluminum titanate which has recently been discontinued).

3.6.3 Economic Parameters -

Economic parameters for 3DP are based on an economic model for precision machine tools developed by Slocum, and estimates of overhaul, salvage, and purchase price of a turnkey 3DP machine equivalent to the MIT Alpha machine (with development costs distributed over several machines). Powder costs are taken from M. Mangin's assessment of
the manufacturing cost of automotive valve train components (MIT PhD, 1993). With these parameters, the database calculates unit manufacturing costs for producing a ceramic preform via 3DP, with any additional post processing costs added to this.
3.7 Results of the Application Survey

This section outlines the top applications selected by the analysis software and give a brief description of their characteristics.

![Diagram of Application Analysis Process]

Figure 3.10

The top ten applications as selected by the analysis software with the 3DP parameters shown above, and product attributes shown on the following pages were, in ascending order of Quality Loss:

- Turbocharger Scroll
- Anatomical models for medical applications
- Paleontological Models
- Compact crossflow heat exchanger core
- Personnel armor
- Contoured grinding wheel
- Phalangal prosthesis
- Laser Mirror Blank
- Metrology Tool Frame
Each of these applications will be described in more detail below. The merits of each of these applications, and the validity of the analysis will be discussed in the following sections.

1. Turbocharger Scroll -

Turbocharging is a method of harnessing the latent energy of IC engine exhaust. This energy is used to compress the intake charge to the cylinders, thereby increasing the power density of the engine. With turbocharging, smaller displacement engines can be substituted for larger, less efficient engines with no penalty in performance. The ultimate in turbocharged IC engines were the powerplants of Formula 1 race cars in the late 80's, where 1.5 liter engines were approaching 1500 hp in qualifying trim (1000 hp/l compared to unturbocharged race engines routinely producing only 200-225 hp/l).

One of the most complex components in the turbocharger is the scroll, or housing. The turbocharger scroll is a nautilus shaped component that directs hot exhaust gasses over the exhaust rotor's vanes before they are vented through the tailpipe. The turbo intake impeller, attached by a shaft through the center of the scroll to the exhaust rotor, compresses intake air and discharges it through a plenum to the individual cylinders. On the exhaust side the scroll sees temperatures on the order of 1000°C and must have sufficient strength and stiffness at this temperature to maintain close tolerances and contain fragments should the rotor burst. With the use of ceramic rotors, currently installed in several models of Japanese vehicles, lighter and less robust ceramic scrolls offer a significant advantage over the current metal designs.

Reliably fabricating the complex curvatures of the scroll from advanced ceramics has proven difficult by other methods (primarily slip casting in the case of the scroll used in the Automotive Gas Turbine developed by Allison Turbine). The metallic components are sand cast and finish machined on critical mating and bearing surfaces.

According to Kraig Heathco of Allison, the 3DP scroll could be slurry honed to give the desired finish on all flow passages, effectively eliminating 3DP's surface finish disadvantages. Turbocharger scrolls for engines in the 1-5 liter range are between 10 and 15 cm in diameter and 5-10 cm in depth, well within the capabilities of the existing 3DP
machines.

Figure 3.11

Twenty-four thousand ceramic-rotor turbocharger equipped automobiles were produced in Japan in 1992. This represents the upper production bound for ceramic scrolls because they are not compatible with metallic rotors (for burst containment). Capturing only 10% (2000 units) of the Japanese ceramic turbo market would require 2 dedicated Alpha-type, or one DSP style printer. A single 3DP Alpha-type printer could produce 1300 scroll preforms per year (10x10x5 cm) running only 2000 hours/yr. The Soligen DSP system could produce approximately 3900 / year / machine. These calculations were made based on 177 micron layers, 8 jets for the Alpha and 40 jets for the Soligen machine, 12x6x12" piston for the Alpha, and 30x30x30cm for the Soligen machine.

2. Anatomical Models -

Physicians, archaeologists, and forensic experts are turning to rapid prototyped physical models of human and animal skeletons for analysis purposes. The ability to review a high quality model of maxillo facial defects is very valuable for planning and teaching corrective surgery. Likewise, creating a model of entombed bodies via scan data without disturbing fragile burial containers could lend new evidence to archeologists while preserving the specimen.38
Anatomical models have highly complex internal and external geometries, low production volumes, and surface quality is of secondary concern. A full scale model of a human skull is approximately 22x12x12 cm, within the build volume of current 3DP systems. Such models should find acceptance in research hospitals, major museums, and forensic research institutions, granted the cost is kept within reason.

3. *Paleontological Models* - See Appendix B for more about this application

4. *Heat Exchanger Core* - See Chapter 4 for more about this application.

5. *Personnel Armor* -

Ceramic armor has been used since the Vietnam War for shielding helicopter flight crews from low caliber ground fire. Typically a plate of boron carbide is backed with a thin sheet of kevlar and enclosed in a cloth bag to catch secondary fragments. A 0.64 cm thick plate of B$_4$C is capable of stopping armor piercing 0.30-caliber projectiles. Other ceramic armor materials are alumina, silicon carbide and TiB$_2$.

The 3DP application is in lightweight ceramic armor for law enforcement officers in high risk assignments (e.g., SWAT). Suits consisting of head, chest, arm, and leg armor tailored to officers of different sizes would offer much more complete and effective protection against hand guns than current kevlar vests. Ceramic plates would be printed
based on measurements of the individual wearer, assuring proper fit for maximum protection.

Of all parameters of concern to the 3DP analysis, only the size and the material composition are problematic. 3DP can create the necessary geometry, and surface finish is not important. Because the armor would be tailored to individuals, 3DP's direct fabrication of preforms would be much less expensive than creating molds for hot pressing or slip casting. Large flat plates for the chest and back would be fabricated by other means while helmet components, shoulder, forearm, and shin pieces can be fabricated via 3DP. These components require compound curves and are more user specific.

6. Contoured Grinding Wheel -

Plunge or form grinding requires that the wheel be dressed to the desired contour in a secondary operation. Conceivably 3DP could quickly produce wheels with the requisite contour already formed into the wheel. More importantly, a 3DP wheel could be printed as a composite with structural ceramic in the center and a region near the radius rich in the more expensive CBN or diamond grains. A ceramic cored grinding wheel is very stiff, has low thermal expansion, and ostensibly would offer increased accuracy.

The contoured grinding wheel requires multimaterial capability, flexible manufacturing (i.e., low volumes of different wheel geometries), multiple material capability, and lax surface roughness requirements (depending on grinding operation). Size could range from small to larger than the print beds of current 3D Printers.
7. Phalangeal Prosthesis -

Replacement of the metatarso phalangeal joint due to disease or trauma has been successfully accomplished with alumina prosthetic inserts. Low wear, bioinertness, chemical resistance, and good strength are the prime material requisites for this application. 3DP is well suited for this application because of the highly individual components, controlled surface roughness for bone ingrowth, and small size make rapid production possible. It is also possible for 3DP to print a preform of the implant in alumina, and subsequently infiltrate it with one of the bioreactive glasses to enhance bone ingrowth.

It has been assumed that the 3DP preform for this application can be finish ground to achieve the 3μm Rₐ joint surface. If this quality of surface is necessary in the green component, it would fall considerably further back in the application comparison.

![Image of a bone prosthesis](image.png)

**Figure 4.14**

8. Laser Mirror Blank -

Silicon carbide blanks for high precision mirrors are used in the production of numerous components for laboratory, space, and military applications. "Large aperture mirrors require tight fabrication tolerances, high thermal conductivity, low thermal expansion coefficients, high stiffness, and low areal mass". Current SiC mirror blanks are fabricated by the Ceraform process. Ceraform freezes slurry in a mold, the mold is removed, and the component is freeze dried before firing.

Mirror blanks range in size from a few millimeters in diameter to over 1.5 m in diameter. Recent large aperture telescopes are modular with dozens of discrete mirror
segments that are actively positioned with actuators to achieve the correct composite curvature.

3DP can compete with the ceraform process, optimizing the design of the blank to achieve the highest stiffness to weight ratio without expensive molds. Because the blank must be finish ground, and coated with reflective material in a multistep process, the surface quality of the initial blank is of lesser importance. Mirrors for laboratory and aerospace applications are well within the size limitations of the current 3D Printers.

9. Metrology Tool Frames -

Precision instruments such as micrometers, calipers, gage blocks, and rules all benefit from the unique properties of ceramics. An extremely stiff, low weight, and brittle micrometer frame has the advantage that it doesn't flex in use, it is easy to handle, and will break if dropped. In the machine shop environment this is unacceptable, but for quality control or in the laboratory, this characteristic assures that a damaged instrument is not used.

For the 3DP analysis this application is small, surface quality is important in only the bearing regions and can easily be honed (the textured surface would ease handling), and the value of such instruments is very high in small quantities.

Related to this are high precision mounts and positioning tables for locating optics in laser systems. High strength, zero coefficient of thermal expansion, high stiffness, and low mass are all attributes attractive to this application. Ultra precision machine tools rely on laser interferometry for accurate axes position information. By increasing the integrity of the
mounting structures for the laser system, fewer errors are carried over to the workpiece.

![Diagram](image)

**Figure 4.15**

### 3.8 Conclusions on Selected Applications

Applications selected by the database software are those which have lower surface quality requirements, relatively low production volumes, complex geometry, and have a need for the properties of advanced ceramics. As mentioned previously, the ability of the Quality Loss methodology to compare an application with the capabilities of 3DP is limited to the resolution of information available. It is believed that the analysis performed here has been useful in highlighting potential applications for 3DP, and in this regard the original goals of the 3DP Application Survey have been met.
4 Example of Using Quality Loss to Compare Processes

As mentioned previously, an interesting application of the Quality Loss analysis method is that it can be used to compare competing processes. To illustrate the point, a product-process combination currently used in industry is compared with 3DP. The goal is to see if the system chooses 3DP or the current process and to learn what attributes of the application cause it to be paired with a process.

Low Pressure Injection Molding (LPM) is currently the preferred method for fabricating ceramic mold cores. A common application of such cores is in investment casting of turbine blades. Technical and economic parameters for both a generic mold core and the LPM process were entered in the spreadsheet, and evaluated against 3DP and ceramic slipcasting.

Effects of variations in process and economic parameters on the bottom line i.e., quality loss and net present value, are investigated using "what if" scenarios. Batch size, equipment cost and lending rate were studied for their effect on unit manufacturing cost (UMC), net present value, and quality loss for the mold core example. Tables 4.2 and 4.3 are the spreadsheet cells showing technical and economic parameters for producing a generic mold core with the LPM process.

4.1 Description of typical Low Pressure Injection Molding Equipment

The Low Pressure Injection Molding Process is virtually identical to conventional ceramic injection molding with one critical difference; the pressures employed are in the range of 0.35 -0.70 MPa (50 - 100 psi) versus the 7 - 70 MPa for conventional ceramic injection molding. Aluminum tooling exhibits minimal wear because of the low injection pressures. Additionally, aluminum tooling is less expensive and can be fabricated more quickly than steel dies. Tools made from conventional tool steels, however, will have an infinitely longer life, again because of the reduced injection pressures.

Following are features of a contemporary low pressure ceramic injection molding system by Pelsman Corp., the Pelsman MIGL-37:
- Production rate up to 750 cycles per hour (times the number of cavities in the die)
- Gate cutting
- Automatic cycle control
- Molding pressure up to 70psi
- Molding Temp up to 300 F
- Maximum size of dies - 19" x 20" x 20"
- Maximum size of cavity - 3x3x3"
- Surface Roughness 1-3 micron $R_a$
- Size tolerance .3 - .7 mm (Ludema et al., "Manufacturing Engineering", pp. 384-5)

Table 4.1 gives additional information on the capabilities of the Peltzman LPM equipment. Note that the density and strength information are for fully dense components. This implies that the green density is on the order of 55 vol % or higher, therefore this number is used in the calculations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Silicon Nitride</th>
<th>Alumina</th>
<th>Alumina/Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>3.29 g/cc (96 % T.D)</td>
<td>3.75 (94%)</td>
<td>3.51 (96%)</td>
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<tr>
<td>Strength</td>
<td>640 MPa</td>
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<td>326 MPa</td>
</tr>
<tr>
<td>Weibull Modulus</td>
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</tr>
<tr>
<td>Failure Origins</td>
<td>Inclusions of FeSi</td>
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</tr>
</tbody>
</table>
The FOB ex-factory price for manual molding machine MIGL-28 is $12,500; for semiautomatic molding machine MIGL-33 is $21,900; for the automatic machine MIGL-37 $43,900.

4.2 Mold Cores -

Information on mold cores for turbine blades was gathered from interviews with engineers in the industry. Because such a variety of turbine blade configurations and sizes exist, the example used in this analysis is intended to represent a mold core for a generic turbine blade. Customer weightings for the weighted quality loss were chosen for this example based on a phone interview with Ron Keller of Howmet Co. Howmet uses LPM exclusively for the production of ceramic turbine blade mold cores. Cost estimates for mold core production were obtained from an engineer from GE Turbine.

4.3 Calculating Quality Loss for the LPM - Mold Core Example

Assumptions made for this example are shown in Tables 4.2 and 4.3 which show product and process parameters. Notable is product value which is based on an interview with an engineer from GE Aircraft Engines. He estimated that the core comprises 10% of the value of an average turbine blade's $1500 cost. Naturally there are many types of blades ranging from very small, high pressure blades to the huge fan blades on high bypass engines. Product parameters used in this comparison are merely representative, and can naturally be changed to reflect the specific dimensions of any component.†

<table>
<thead>
<tr>
<th>Table 4.2: Product Parameters for Turbine Blade Mold Core Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Attribute</strong></td>
</tr>
<tr>
<td>Size</td>
</tr>
<tr>
<td>Geometry Category</td>
</tr>
<tr>
<td>Surface Roughness</td>
</tr>
</tbody>
</table>

† For this comparison, Phadke's equations are used and not the improved equations described in section 3.3.3
Table 4.3: Process Parameters for Mold Core Example

<table>
<thead>
<tr>
<th>Process Capability</th>
<th>LPM</th>
<th>3DP</th>
<th>Slip Cast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Size</td>
<td>300</td>
<td>7,500</td>
<td>15,000</td>
</tr>
<tr>
<td>Min Size</td>
<td>0.02</td>
<td>0.02</td>
<td>1</td>
</tr>
<tr>
<td>Min Wall Thickness</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Max Geometry Category</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>1.5</td>
<td>25</td>
<td>0.8</td>
</tr>
<tr>
<td>Dimensional Tolerance</td>
<td>0.3</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Green Strength</td>
<td>2.5</td>
<td>3.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Green Density</td>
<td>55</td>
<td>37</td>
<td>55</td>
</tr>
<tr>
<td>Locatable Secondary Material</td>
<td>0</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Equivalent Build Rate</td>
<td>450</td>
<td>0.21</td>
<td>0.4</td>
</tr>
<tr>
<td>Equipment Cost</td>
<td>48,000</td>
<td>200,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Material Cost</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Die Costs</td>
<td>10,000''</td>
<td>0</td>
<td>10,000</td>
</tr>
</tbody>
</table>

† Estimated
++ Die costs are a strong function of complexity

Values shown in **bold** in tables 4.2 and 4.3 are to be entered by the user, all others are automatically calculated. Parameters such as equipment cost and size are entered in spreadsheet cells not shown here. On the following page is a full view of the spreadsheet of the spreadsheet as it appears in Excel.
Below are the quality loss values generated for the LPM - mold core parameters using the equations described in the previous section. By the nature of the product/process characteristics used in this analysis, all loss calculations are either Bigger is Better or Smaller is Better.

<table>
<thead>
<tr>
<th>Table 4.4: Quality Loss Values Generate for the Mold Core Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality Loss</td>
</tr>
<tr>
<td>LPM</td>
</tr>
<tr>
<td>Loss</td>
</tr>
<tr>
<td>Size</td>
</tr>
<tr>
<td>Geometry Category</td>
</tr>
<tr>
<td>Surface Roughness</td>
</tr>
<tr>
<td>Dimensional Accuracy</td>
</tr>
<tr>
<td>Green Strength</td>
</tr>
<tr>
<td>Green Density</td>
</tr>
<tr>
<td>Secondary Material</td>
</tr>
<tr>
<td>Production Volume</td>
</tr>
<tr>
<td>Profit</td>
</tr>
</tbody>
</table>

As an example, the value in the upper left cell for loss associated with the size of the product is calculated in the following manner:

\[ \text{Loss} = \frac{\text{Core Size}^2}{\text{Maximum Product Size}^2} \]

\[ \text{Loss} = \frac{(250)^2}{(300)^2} = 0.694 \]

A Bigger is Better loss calculation is used for this parameter because as the maximum size capacity increases, the equipment is able to handle not only larger components, but also a larger number of cavities for small high production volume parts. A loss of 0.694 represents
a process capability which meets the requirements for the mold core with a moderate amount of overcapacity.

A second example is the loss associated with the desired profit margin for the mold core assuming that only 100 cores per year are desired at $125 each.

\[
Loss = \frac{(1 + \text{Profit margin})^2}{(\text{Product Value/ Production Cost})^2}
\]

\[
Loss = \frac{(1.2)^2}{(125/128.87)^2} = 1.53
\]

A loss of 1.53 indicates that the process, with the given parameters, was unable to meet the desired profit margin, thereby incurring an increased loss. Increasing the order size to 1000, as shown in the printouts, lowers the loss to only 0.105 because the die costs are distributed over more products.

### 4.4 Results of Mold Core Example

This methodology is capable of selecting the proper manufacturing process for a given product. In this study, the software correctly identified Low Pressure Injection Molding for ceramics as the process of choice for manufacturing ceramic mold cores. This study was limited, however, to a comparison between only three competing manufacturing processes. Additionally, this comparison uses Phadke's equations and not the improved methods for Bigger is Better and Smaller is better discussed in section 3.3.3. A more complete comparison should include detailed information on further ceramic forming processes such as dry pressing, hot pressing, green machining, and isostatic pressing.

Looking at Table 15, it is shown that the average quality loss for LPM is 0.44 compared to 1.58 for 3DP/8† and 0.71 for Slip Casting. Considering the wishes of a customer such as Howmet, the weighted loss for LPM, 3DP, and Slip Casting are 26.25, 62.85, and 31.51 respectively.

<table>
<thead>
<tr>
<th>Table 4.5: Quality Losses Calculated for the Mold Core Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>3DP/8 refers to Three Dimensional Printing with an 8 nozzle printhead</td>
</tr>
</tbody>
</table>

†
<table>
<thead>
<tr>
<th>Table 4.5: Quality Losses Calculated for the Mold Core Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPM 3DP/8 Slip Casting</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>0.44</td>
</tr>
<tr>
<td>26.25</td>
</tr>
</tbody>
</table>

According to the loss scores above, remembering that lower is better, LPM is both the best process based on purely technical and economic reasons, and the best at meeting the customer's wishes under the given circumstances. Reasons why 3DP did not fare well for this product are clarified in Table 4.4, which shows a large loss for 3DP's slow production rate and surface roughness.

Figures 4.2 and 4.3 show how this methodology is able to depict trends for the LPM process, reflecting both technical and economic considerations. Figure 4.3 depicts Quality Loss trends for each process. 3DP leads for low production volumes because there are no die costs, but falls behind as production volume outruns it. LPM in contrast is expensive for small batch sizes due to high die costs, but quickly takes the lead as die costs can be spread over more products. Slip Casting has a global minimum around 1000 units/year, but never becomes a competitor with the other processes because of low production rate and high initial costs. Figure 4.4 shows the manufacturing cost trends for each process. Where LPM and Slip Casting are both batch size dependent, 3DP's unit manufacturing costs remain constant because it's costs are associated with materials, equipment and operator wages which do not fluctuate with batch size.

† A large loss indicates that this process parameter should be improved, if possible, or the product needs to be redesigned to conform to the capabilities of existing manufacturing equipment.

†† All of these figures were generated with the product/process parameters shown in Tables 12 and 13.
Figure 4.2 shows the quadratic nature of the Quality Loss related to dimensional accuracy for the mold core example. The plot represents a reduction in loss as the product specification for dimensional accuracy becomes more lax (i.e., larger tolerances), remembering that the process parameter for dimensional accuracy is fixed†. Similarly, Figure 4.2 shows how products with increasingly rough surfaces (higher Roughness values) have a lower quality loss. This plot also stresses the superiority of the LPM process over 3DP with regards to surface quality.

† Of course these plots could be generated using a fixed product parameter while varying the process capability.
4.5 Analysis Software Conclusions

This methodology is an extremely powerful tool for investigating how an arbitrary process is suited to produce an arbitrary product. Furthermore it has shown its ability to select the optimal process and optimal process and economic parameters. Without substantial modification to the existing software, parameters such as material selection, thermal considerations, or environmental limitations could be included in the analysis to meet the individual needs of the customer. Flexibility to grow and perform well for a variety of users from composite processing to candy wrapping is the greatest asset of this methodology.

Verification of this methodology was performed using process parameters for the three competing processes garnered from a variety of sources. Because there exists a
plethora of equipment variations for Slip Casting and, to a lesser degree, LPM, the values
entered in the spreadsheet are only representative.

4.5.1 Weaknesses of the Application Analysis Methods

First and foremost of the weaknesses of this approach are that there has been only a few creative minds suggesting novel applications for inclusion in the analysis process. The majority of applications explored were suggested by the author based on a search of the literature and periodicals. The list of applications is certainly by no means exhaustive, representing only a fraction of the marketable "special interest" applications internal to many companies. Section 6.5 briefly touches on a proposed solution for increasing the number, and quality of applications through using the analysis software to educate designers about the strengths and limitations of 3DP.

The greatest weakness of both the early Pugh Filter methods and the Quality Loss approach is that the quality of analysis results are a direct function of the quality of input information. In contrast to the subjective nature of the Pugh methodology, however, the Quality Loss method is completely objective in its analysis, based purely on the comparison between process capabilities and product engineering characteristics. Areas where the usefulness of the Quality Loss Method are degraded, however, are:

- **Broad spectrum of values for a given product attribute** (ie surface quality in a mold: in the case of a stippled, or textured mold, the Ra value is high but the surface quality is very good.)
- **Proprietary or undocumented product attributes**: military applications, enabling technologies, etc.
- **Novel applications of a material**: in the sense that no example of what a product's engineering characteristics would be in ceramic instead of metal (i.e. using zero thermal expansion ceramics for sensitive measuring equipment components).

To overcome these limitations, guidelines for those characteristics in question were inferred from standard manufacturing practices. For example, if a component were typically produced via injection molding, it is logical to infer that the surface quality of the 3DP counterpart should be comparable to that of an average injection molding die.

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5 Ceramic Heat Exchangers

5.1 Introduction-

Advanced ceramics are the logical answer to demand for economical heat exchanger components which can withstand corrosive exhaust streams in excess of 1000 °C. High temperature ceramic heat exchangers are available in a variety of sizes and configurations depending on the application. The most common configurations are the shell-in-shell, plate-fin, tubular, fluidized bed, and heat pipe recuperators. The most interesting for 3DP is a subsection of the plate-fin variety known as Compact Core Heat Exchangers (CCHX).

The figure below shows a GTE compact cross-flow exchanger of the type used in recuperating hot waste gas energy in the metal and glass industry. Compact core recuperators (recuperator will be used interchangeably with heat exchanger) are classified by the path the gas streams are to follow: co-flow, counter flow, and cross flow. Cross flow compact core exchangers are more difficult to fabricate because their complicated geometry precludes the use of extrusion techniques. Details on current fabrication methods are given later in this section.

In comparison to their metallic counterparts, ceramic heat exchanger components offer good strength up to bulk material temperatures of 1300 °C, and have substantially greater corrosion resistance. This gives ceramics a two-fold economic advantage over metals: greater efficiency at higher temperatures, and less frequent replacement due to corrosion. A comparison of metals and generic ceramics is given in Table 5.1.

<table>
<thead>
<tr>
<th>Recuperator Material</th>
<th>Maximum Flue Gas Temperature, °C</th>
<th>Cost for ft² of Heat Exchanger Surface</th>
<th>Burner Inlet Temparture, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Effectiveness = 0.4</td>
<td>Effectiveness = 0.7</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>454</td>
<td></td>
<td>204</td>
</tr>
<tr>
<td>Low-Alloy Steel</td>
<td>592</td>
<td>$10</td>
<td>259</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>815</td>
<td>$20</td>
<td>348</td>
</tr>
<tr>
<td>Nickel Alloys</td>
<td>1,092</td>
<td>$40</td>
<td>459</td>
</tr>
</tbody>
</table>

Table 5.1 Comparison of Metals to Ceramics for Heat Exchanger Application
(Source: Cobrough L.; Compact Ceramic Heat Exchangers, Coors Ceramics 1985)
### Table 5.1

<table>
<thead>
<tr>
<th>Recuperator Material</th>
<th>Maximum Flue Gas Temperature, °C</th>
<th>Cost per ft² of Heat Exchanger Surface</th>
<th>Burner Inlet Temperature, °C</th>
<th>Effectiveness</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramics</td>
<td>1,369</td>
<td>$ 40</td>
<td>592</td>
<td>0.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Temperature limits will differ with exact material composition, dollars in 1979 dollars

### 5.2 Industrial Demand

A myriad of industries depend on high temperature processes for producing engineering materials or altering their state. These processes are inherently energy intensive, thereby adding substantially to the overall cost of production. As new processes require ever higher temperatures, energy costs skyrocket.

#### Waste Heat Recovery

In a study conducted by the EPA it was estimated that "23% of major or energy intensive industrial fuels and electrical energy consumption is discharged as waste heat in flue gases." In an effort to reduce these numbers the DOE has funded research to develop systems which increase the overall efficiency of furnaces and other high temperature applications. One approach that has been very effective is recuperating hot waste gas energy with Compact Ceramic Heat Exchangers (CCHX).
From Table 5.2 and Figures 5.2 and 5.3 it is clear that the largest overall efficiency gains can be obtained from reducing or recycling the energy wasted up the exhaust flue. As shown above, the concept of the recuperator is to transfer heat energy from the exhaust flue to the intake stream, thereby reducing the fuel necessary to heat the intake gases to operating temperatures. Fuel savings of greater than 30% have been reported for recuperated systems over their unrecuperated counterparts in the glass and metal industries.

Table 5.3 illuminates the scope of the industrial waste heat recovery market. Between the various segments there are 17,880 furnaces of which only 5717 (32%) are
recuperated. More recent data on the total number of high temperature furnaces potentially benefiting from recuperation was not available.

<table>
<thead>
<tr>
<th>Furnace</th>
<th>Consumption (kJ) (year)</th>
<th>Number of Furnaces</th>
<th>Percent of Population Recuperated</th>
<th>Flue Gas Temp (^\circ)C</th>
<th>Average Firing Rate, (\text{mm W})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Soaking</td>
<td>160 (1979)</td>
<td>2,275</td>
<td>85 - 90</td>
<td>815-1371</td>
<td>7.3</td>
</tr>
<tr>
<td>Steel Reheat - continuous - batch-type</td>
<td>351 (1979)</td>
<td>310</td>
<td>60</td>
<td>1315-1426</td>
<td>72.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>385</td>
<td>30</td>
<td>815 - 1371</td>
<td>11.6</td>
</tr>
<tr>
<td>Iron and steel forging - slot forge - car bottom and box</td>
<td>89 (1980)</td>
<td>8000</td>
<td>15</td>
<td>1315-1426</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4500</td>
<td></td>
<td>815 - 1426</td>
<td>1.514.5</td>
</tr>
<tr>
<td>Glass melting - unit melters - regenerative</td>
<td>189 (1979)</td>
<td>800</td>
<td>95</td>
<td>1426-1537</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75</td>
<td></td>
<td>1426-1537</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>725</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum reverberatory furnace</td>
<td>51 (1978)</td>
<td>800</td>
<td>5</td>
<td>760 - 1260</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.6</td>
</tr>
<tr>
<td>Copper reverberatory furnace</td>
<td>18 (1976)</td>
<td>12</td>
<td>8</td>
<td>1315-1426</td>
<td>33.3</td>
</tr>
</tbody>
</table>

Table 5.3: Industrial Waste Heat Recovery Market


Of industrial energy consumers, the steel, aluminum and glass industries are the largest and represent the greatest challenge to recover their waste heat because of the harshness of these environments. In common applications flue gas temperatures can reach 1650 \(^\circ\)C, and have high fouling and extremely corrosive properties.\(^{33}\) For this reason, ceramics are the natural choice for heat exchangers operating in this type of environment. Figure 5.5 shows the fuel savings attendant to rising exhaust temperatures. Ceramic heat exchangers allow temperatures to be pushed into the higher regimes where other materials are unable to perform. Based on these fuel savings, typical payback for the investment in
Case study of Compact Ceramic Recuperator (Section excerpted directly from 34 p.7)-

XTEK Inc., Cincinnati, OH anneals, carburizes and/or heat treats 26,000,000 pounds of product annually and consumes 76 600 000 cubic feet/year of natural gas. To reduce energy related production costs, a cylindrical retort atmosphere control-type pit furnace (20' x 10.5' OD 6'ID) was retrofitted with twelve compact core ceramic recuperators. This furnace operates 24 hours a day, 6500 hours per year at temperatures between 840 C and 954 C. Annual fuel consumption before recuperation was 12,000,000 cubic feet of natural gas.

Operating Conditions-  
Recoup. air intake  
Recoup. exhaust inlet  
Excess Air Rate  
Exhaust Flow rate  
Air flow rate  

38 C  
954 C  
20%  
4800 scf/h  
4400 scf/h
System Economics - The total retrofit installed costs were $116,830 (1982), reported savings were 60.7%. This amounts to $42,111 annual savings resulting in a simple payback of 2.8 years.

5.3 CCHX Market Conclusions

Despite the drastic reduction in fuel costs for recuperated furnaces, the market for compact core heat exchangers has declined since the initial market study at the beginning of the 3DP Application Survey. A follow up interview with Lloyd Sobel of Coors Ceramics revealed that Coors has ceased production of their compact core heat exchanger line, and have suspended production of the MTF-4 Aluminum Titanate developed specially for this application. It was unclear from the interview what factors played a role in Coors' retreat from the market. GTE-Osram, however, still supplies users with new systems and replacement cores.

5.4 Design and Construction -

This section will concentrate on the design and construction of the compact core cross flow heat exchanger. Compact ceramic heat exchangers are defined as those that have a high heat transfer area to volume ratio, on the order of 230 m²/m³. Increasing this ratio increases the convective heat transfer of the unit but, with the attendant decrease in flow passage cross section, raises the pressure drop across the core.

Typical cross flow CCHX units marketed by Coors Ceramic, Golden CO, and GTE (now Osram Sylvania) range in size from 10x10x10 inches to 12x12x18". Table 5.4 shows prices and performance for current Osram Exchangers. Flow passages are universally rectangular, approximately 0.125" x 0.20 " in section, and partitions between passages can be as thin as 70 mils.(Vincenzini).

<table>
<thead>
<tr>
<th>Model</th>
<th>Btu/hr</th>
<th>Size</th>
<th>Core Price ($)</th>
<th>Complete Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-600</td>
<td>600,000</td>
<td>10x10x10&quot;</td>
<td>1,900</td>
<td>4,420</td>
</tr>
</tbody>
</table>

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5.5 Materials

Ceramic recuperator cores are constructed from cordierite - 2MgO-2Al₂O₃-5SiO₂, or aluminum titanate - Al₂TiO₅, because of ease of fabrication, relatively low thermal expansion, good thermal shock resistance, and corrosion-resistance characteristics.

Table 5.5: Material Properties for Cordierite, MTF-4, and Al₂O₃
(Source: Coors Structural Ceramics, Golden Colorado, 1991 STD 990)

<table>
<thead>
<tr>
<th>Property</th>
<th>Cordierite</th>
<th>MTF-4 (Aluminum Titanate)</th>
<th>Alumina (99.5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>2.51</td>
<td>3.1</td>
<td>3.89</td>
</tr>
<tr>
<td>Flex. Strength (MOR) (MPa)</td>
<td>117</td>
<td>25</td>
<td>379</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>3</td>
<td>1</td>
<td>35.6</td>
</tr>
<tr>
<td>Max Useful Temp (°C)</td>
<td>1,371</td>
<td>1,427</td>
<td>1,750</td>
</tr>
<tr>
<td>Coeff. of Therm. Exp (x10⁻⁶°C)</td>
<td>1.7</td>
<td>0.7</td>
<td>8.2</td>
</tr>
<tr>
<td>Thermal Shock Resistance ΔTc (°C)</td>
<td>500</td>
<td>1,000</td>
<td>250</td>
</tr>
</tbody>
</table>

The aluminum titanate material (MTF-4) developed by Coors Ceramics is superior to cordierite for high temperature heat exchanger applications due to its high thermal shock resistance and low thermal expansion.

5.6 Manufacturing Processes

Cores are manufactured by three methods: 1) bonding ribs to tape cast sheets (the bonding agent is also a cordierite ceramic material), the sheets and ribs are arranged to form a cross-flow heat exchanger, and are bonded to form a monolith (see Fig. 5.6), or 2) ribbed sheets are slip cast, arranged into a layered structure, and then bonded to form a monolith.
3) extruding ribbed plates which are then stacked and boned to form the monolith. Bonding preformed layers is labor intensive and limits geometry to fairly simple shapes. An advantage, however, is that creating exchangers of different widths is a matter of bonding more layers, and that these processes are well understood.

### 5.7 Example of a current design

An industrial recuperator consists of the ceramic core, a resilient fibrous refractory seal, and a metallic housing (Fig. 5.8). A key feature of present GTE recuperators is that the preheat air makes three passes in the recuperator while the exhaust gas passes through once. The areas of each pass are selected to optimize the heat transfer for a given pressure drop. The triple-pass recuperator is a distinct improvement over the earlier single-pass model because the air preheat temperatures are considerably higher. An added advantage of the triple-pass recuperator is that the maximum temperature difference between the exhaust gasses and the preheat air is reduced. Temperature-induced stresses are therefore lower, thus increasing the reliability of the recuperator. 25

Recuparators for waste heat recovery have a finite life due to fouling in soot laden exhaust flue gasses, and thermal cycling induced fatigue causing structural failure. In the
Figure 5.7

Figure 5.8 Assembling a cross flow exchanger
(Vincenzini, P. High Tech Ceramics, Elsevier Science Publishers, Amsterdam, 1987)
case of compact core exchangers, the entire core must be replaced once a threshold value for blowby from exhaust to intake side has been reached, or the back pressure due to fouled passages becomes too large. As can be seen in the Figure above, GTE uses a modular design to accommodate exchange of cores, which can be accomplished in approximately one hour.

Figure 5.9

5.8 3DP Fabrication of Heat Exchangers

Three Dimensional Printing holds considerable promise for fabricating compact ceramic heat exchangers that are both more efficient and less expensive than current tape cast or slip cast models. 3DP's extreme flexibility in creating components with complex internal geometries makes fabrication of next generation heat exchangers having higher efficiencies, and reduced back pressure possible. Additionally, location specific material
composition could give performance enhancements in strength, thermal shock resistance, and corrosion resistance.

This section discusses issues surrounding fabrication of high temperature heat exchanger cores via 3DP, and describes results of the design and fabrication of demonstration components. Important achievements in this area are demonstration of high strength, hermetic components, in a cross flow configuration. Future work in this area will be in materials development to achieve the required thermal shock resistance, and high temperature strength necessary for CCHX applications.

5.8.1 Manufacturing Heat Exchanger Cores with 3DP

As described in the analysis section, compact ceramic heat exchanger cores are a technically interesting application because:

- they are not limited by 3DP's current surface quality
- they stand to benefit from 3DP's ability to create arbitrary geometry, and
- 3DP's point to point materials flexibility could improve performance

The obvious challenge to 3DP manufacturing heat exchanger cores are their size. Not only does this require a larger build volume, but also a considerably faster build rate than currently possible, both issues necessitating the design of a new 3D Printer. Test components were fabricated to show the various capabilities of 3DP and ho

5.8.2 Test Component Design

Test components were fabricateed that show off 3DP's potential for heat exchanger applications. Various geometries and material compositions were fabricateed to show the range of possibilities 3DP offers. Each is described in more detail below.

5.8.2.1 Cross Flow Matrix-

This group of components mimic the geometry of the GTE and Coors compact cross flow recuperators shown in the previous section. This geometry, as mentioned previously, is difficult to fabricate by traditional methods, and is limited to relatively simple internal passage configurations. Figure 5.10 shows this component used to demonstrate infiltration
techniques for reaching full density. (Progress in infiltration techniques for densifying 3DP preforms is handled in Chapter 5) This geometry is similar to that used in the GTE and Coors systems, but differs in that it is a true monolith, fabricated in a single processing step. Manufacturing it as a monolith reduces the likelihood of failure due to fracturing of the core along the ribs.

![Figure 5.10](image)

Figure 5.11 shows FEA analysis results for the Coors MTF-4 (aluminum titanate) CCHX. Notice that the maximum stress is concentrated at a rib's mid section on the exhaust inlet side. Although it has not been demonstrated, it is conceivable that redesigning the rib geometry could reduce maximum stresses, enabling the use of a wider variety of materials. With the use of rapid manufacturing, designers can quickly iterate designs to minimize such stress concentrations. Perhaps a change in geometry would have allowed Coors to use a
more mundane material opposed to developing a new aluminum-titanate for this application.

\[ \text{Figure 5.11} \]

5.8.2.2 Flow Passage Optimization-

Controlling flow passage design, such as twisting ribbon, surface texture, and vanes, is used to greatly increase efficiency and reduce back pressure in metallic heat exchangers.

Heat Transfer Augmentation - Surface Geometries

Turbulent heat transfer in gas/gas heat exchangers can be greatly increased by increasing the aA factor (\( \alpha = \text{heat transfer coefficient}, \ A = \text{heat transfer surface area} \)). Methods that increase \( \alpha \) without increasing the exchanger area are: surface roughness and turbulence promoters. Surface area increase is provided by extended or finned surfaces.\(^\dagger\) Finnedor specially formed surfaces may also provide higher heat transfer coefficients due to reduced hydraulic diameter or the establishment of reduced boundary layer thickness. An example of this is interrupted fins for single-phase forced convection.\(^1\)

According to Webb, the most effective heat transfer augmentation method for turbulent flow in passages are helical ribs. Exact rib geometry is dependent upon the operating parameters of the application. After extended surfaces, the most effective transfer augmentation method is a "sand grain" type surface roughness. Tests by Fenner and Ragi

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\(^\dagger\) Webb, Ralph., "Surface Geometries for Heat Transfer"

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show that with water (Re = 35000, Pr = 10, e/D = 0.012) surface roughness covering 50% of the projected surface increases heat transfer by 110% with a 78% efficiency index.

Table 5.5 shows relative performance gains using different augmentation methods. The performance measures, V/V, UA/UA, G/G, and P/P, are stated relative to a smooth tube exchanger designed for the same operating conditions.†

<table>
<thead>
<tr>
<th>Augmentation Geometry</th>
<th>Material Reaction</th>
<th>Increased Heat Transfer</th>
<th>Reduced Pumping Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V/V, G/G, e (mm)</td>
<td>n UA/UA, A G/G, e (mm)</td>
<td>n P/P, G/G, e (mm)</td>
</tr>
<tr>
<td>Two dimensional rib</td>
<td>0.54**</td>
<td>1.28**</td>
<td>0.64</td>
</tr>
<tr>
<td>roughness (p/e = 10)</td>
<td>1.3</td>
<td>0.19</td>
<td>1.4</td>
</tr>
<tr>
<td>Internal fins β = 0</td>
<td>0.88**</td>
<td>1.22**</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>1.22</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Internal fins β = 20</td>
<td>0.69**</td>
<td>1.15</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>1.36**</td>
<td>1.5</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Re = 25000, Pr = 3, tube ID = 17.78 mm, wall = 0.71 mm (e = 0, r = 0.5)

Where: p is axial fin spacing, e is height of fin or roughness element, A is heat transfer surface area, U = is overall heat transfer coefficient, V = volume of heat exchanger tubing material, and G = mass velocity in tube (kg/s). Subscript s connotes smooth surface.

Shown in Figure 5.12 is an example of how 3DP allows the optimization of internal passages in any material. Note that the passages both change cross section and twist from the front to the rear of the block (fabricated in 316 stainless steel).

| Figure 5.12 |

† U = overall heat transfer coefficient, P = pumping power, A = heat transfer surface area, subscript s indicates smooth tube.
5.8.2.3 Integral Manifolding-

Designed with an integral flange and manifold, these components would reduce problems associated with maintaining seal between metal and ceramic components. Manufacturers of 3DP exchangers have the flexibility to incorporate whatever flange design necessary to properly mate with a customer's existing setup. This reduces both the total cost of retrofitting existing equipment with 3DP exchangers, and installation time. Once again demonstrating material flexibility, Figure 5.13 is 316 stainless steel (in the green state), and Figure 5.14 below is 30mm platelet alumina bound with colloidal silica.
Figure 5.14

It is interesting to note that there is no current ceramics manufacturing process capable of fabricating the components shown in Figures 5.12 - 5.14 in a single step, with no hard tooling, in such a range of materials.

5.9 Other Areas of Use for High Temp Heat Exchangers

Outside furnace applications, high temperature heat exchangers are finding use in recuperating gas turbines. Waste heat from the combustor is passed through a heat exchanger transferring energy to the intake stream. As with the furnace applications, this reduces the fuel necessary to reach process temperatures, greatly increasing overall efficiency. Of particular interest are recuperators used to boost hybrid electric vehicle Alternate Power Unit (APU) performance.

Development of the 3DP CCHX is directly beneficial to hybrid-electric vehicles using turboalternator APUs and high temperature fuel cells. Ceramic heat exchangers offer
significant weight savings and higher operating limits over their metal counterparts, but manufacturing costs and reliability have reduced their viability in the hybrid vehicle market. Interviews with industry experts indicate that 3DP ceramic recuperators have potential if the typical limitations of ceramics can be overcome.

Information gleaned from an interview with Paul Craig of Nomac Energy Systems, Tarzana CA, revealed that a ceramic recuperator core for a 25kW turboalternator could shave 20-40 lb. off the recuperator weight (assuming an equal volume of material used as the current stainless steel unit). The recuperator weighs 70lbs comprising approximately 50% of the APU's total weight. A 3DP printed cordierite (2.51 g/cc) recuperator of the same design would reduce the recuperator's weight by 46 lb (66%). Cost analysis of printing such a core (15"OD, 8" ID, 24" L) in quadrants on a modified 3DP machine (to accommodate the large size), estimate a cost approximately 4 times that of the current unit. Enhancements to the 3DP process (discussed later) should lower this cost differential even further, making a 3DP CCHX competitive for this application.

Jim Nash of Northern Research and Engineering Corporation (NREC) Woburn, MA, who is in charge of heat exchanger / recuperator development, corroborated Paul Craig's assessment of the merits of a 3DP CCHX. Application to hybrid vehicles is promising if manufacturing costs can be brought down to a level where they are competitive with current metal exchangers. If thermal shock can be overcome with zero c.t.e. ceramics or mechanical toughening techniques (e.g., whiskers) and production rates were increased, ceramics would find more widespread acceptability.

The 3DP CCHX has the highest probability of finding near-term use in a hybrid vehicle because of its simple design, and relatively relaxed requirements concerning surface quality and dimensional accuracy. Demand for a light-weight, high-performance recuperator for both turbine and fuel cell APUs is high, considering the fanaticism designers exhibit for reducing vehicle weight and improving energy efficiency.

Interviews with Paul Craig of NoMac Engergy Systems revieved that the 25kW APU for a Hybrid Electric Bus requires recuperation to achieve acceptable efficiency.
The current recuperator is a cylindrical stainless steel unit which conforms to the outside of the turbine. Weight sensitive applications such as electric vehicles and aircraft benefit greatly from the substitution of low mass ceramics. Ceramics will not, however, find application in man rated aircraft until the reliability of ceramic components is greatly improved.

5.10 Conclusions -

Test components demonstrating 3DP's ability to address the geometry challenges of high temperature compact heat exchangers were fabricated in both steel and ceramic. Monolithic heat exchanger cores with special features such as integral flanges, manifolds, and improved passage design are easily fabricated with 3DP and represent a marketable advantage over traditional ceramic forming processes.

One area, however, that requires further research is in locating an infiltrant capable of withstanding common high temperature heat exchanger applications. The inceram glass, covered fully in section 6.2.1.4, melts at approximately 800 C. There are glasses, however, which hold great promise for meeting both the fabrication and usage temperature requirements.
6 3DP Process Enhancements

6.1 Introduction

One of the original goals of the 3DP application survey was to use the information gleaned from market analysis, and the experience gained from fabricating test components, to suggest process enhancements to increase the marketability of 3DP. This section will cover four areas of progress which would have an impact on commercialization of 3DP: materials research, work done on a next generation printhead, arguments for the development of a large build volume, high speed printer, and suggestions for possible machine enhancements.

6.2 Materials Research Introduction-

This section outlines material systems evaluated for 3DP structural applications, and comments on achievements as well as guidelines for future work in this area. One of the project's goals is to fabricate demonstration components based on the analysis software's findings. Therefore, it was decided to proceed with fabricating a component representing a section of a high temperature heat exchanger core. Alumina-glass composite specimens have been fabricated having the following material properties: greater than 95% dense, four point bend strength of 230 MPa, thermal diffusivity of 0.0247 cm²/s, hermeticity, and exhibit total shrinkage of less than 2% from green component to full density.

6.2.1 Material Systems Evaluated

Three material systems were evaluated for possible use in creating complex structural components via 3DP 1) spray dried powder achieving high density after isopressing 2) direct fabrication: needing only heat treatment for full density 3) 3DP fabrication of a preform which is subsequently infiltrated with a secondary material to achieve hermeticity and / or full density.
6.2.1.1 Spray Dried Powder and Post Densification

To achieve good densification, the powder must be very fine, i.e., <1μ. Fine powders are, however, more difficult to handle, making their use in the 3DP process problematic at best. A solution is the use of spray dried powder, which alleviates many of the material handling problems, allows full densification (with isopressing), and incurs only a slight cost increase over the use of fine powders.

**The Need for Fine Powders**

To achieve full density, individual ceramic particles in a green preform must fuse together during sintering, closing all void space. This phenomenon is driven by the surface energy of the ceramic particles, a function of the powder's surface area. Therefore powders with high surface energy, i.e., high surface area, are necessary for achieving full density. Fine powders have the requisite surface area to allow complete sintering.

**Problems With Fine Powder**

Fine powders exhibit several traits which make them difficult to use in the 3DP process. Current 3DP powder spreading technology relies on a device similar in function to a baker's flour sieve, where a rotating scraper pushes powder through a stationary mesh. The mesh must necessarily be slightly larger than the size of the powder to allow passage, but no so large as to let the powder pour through continuously. In the case of fine powders, however, agglomerates are easily formed which can no longer pass through the smaller sized mesh. This makes the use of the existing powder dispensing technology problematic and unreliable.

Similarly the formation of agglomerates in fine powders degrades it's spreadability. The counter rotating spreading rod on the 3DP Alpha printer is unable to properly distribute powder over the entire piston when agglomerates are present.
Typical results of using powder with poor spreading characteristics are torn layers, incomplete spreading of layers, and low packing density.

*Spray Dried Powders -*

Spray dried powders offer an alternative to using fine powders for achieving fully dense 3Dprinted components. Spray drying fine ceramic powder creates hollow spherical particles many times the size of the individual original particle. The current practice uses 2 weight percent Poly Acrylic Acid (PAA) as the spray drying polymer because it is not soluble in water.

Advantages of spray dried powder for the 3DP process are its excellent handling properties. The large spherical particles are highly flowable and easily spread by the existing counter-rolling technique. Packing density of the powder bed is higher because the multimodal particles. Powder removal from the internal cavities of spray dried 3DP components is also greatly simplified because of the powder's flowability.

After printing the green body is subjected to isostatic pressing to achieve a higher density before sintering. During compaction the individual spray dried spheres are shattered reproducing the original fine particle size needed for achieving full density. With the density now at 60+ %, the component can be fired to over 90 % of theoretical density.

*Problems Encountered-*

Despite spray dried powder's excellent handling characteristics, it was quickly discovered that densifying complex geometries with internal cavities is a difficult challenge. In typical isopressing operations (either hot or cold), the porous preform must be encapsulated to prevent penetration of the pressing media into the component. This is done either with an elastomeric bag conforming to the outside of the component or a metal "can" in the case of hot isostatic pressing. Both of these, methods, however,

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3DP uses water-based binder to create geometry.
do not accommodate internal passages or components with drastic surface deviations (e.g., spines, or points).

After a review of the literature and interviews with several companies doing contract isopressing, it was determined that no inexpensive densification process for this type of component is readily available. Complex ceramic turbine components are routinely hot isostatic pressed using a proprietary "canning" method, but is uneconomical for most applications.

6.2.1.2 Direct Fabrication

Direct fabrication has a large advantage over multi-process fabrication in that post processing steps such as isostatic pressing and/or infiltration are eliminated. It is achieved by printing into glass-ceramic powders which can then be fired and ceramed to create a fully dense component. The process cycle for manufacturing structural components directly with glass-ceramic powder is the following:

1. CAD model
2. Print component
3. Remove excess powder
4. Fire component to densify
5. Controlled firing to crystallize glass and form ceramic phase

Preliminary tests conducted by Daniel Nammour of MIT with 35-40 mm spraydried feldspar-nepheline dental glass-ceramic. The dental ceramic was debound at 450° C before printing and subsequently fired to 950° C 1 hour to create fully dense glass.
Finally the glass is ceramed using manufacturers data for process parameters. As of this report a fully dense gear has been printed exhibiting 38% linear shrinkage.

**Figure 6.2**

- **Porous Alumina Preform**
  - 45-60% dense

- **During Infiltration @ 1100°C glass ceramic wicks through preform**

- **Fully infiltrated with glass ceramic**
6.2.1.3 Liquid Melt Infiltration

This method is fundamentally different than printing into glass-ceramic in that 3DP is used to create a shape-giving preform of the component. Mechanical strength comes from infiltrating this preform with glass ceramic, effectively creating a ceramic composite. See Figure 6.1 above for process steps.

6.2.1.4 3DP /In-Ceram Components

Glass infiltration tests were conducted on 3DP printed bars using the In-Ceram commercial dental glass-ceramic produced by Vita (see section 6.2.3 for more details on the In-Ceram glass). Three candidate material systems have been printed and infiltrated to date (shown in Table 6.1.)

<table>
<thead>
<tr>
<th>Material</th>
<th>Binder</th>
<th>Sintered density of 3DP Preform Prior to Infiltration</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mm Spherical alumina</td>
<td>6 vol% Acrysol</td>
<td>48%</td>
</tr>
<tr>
<td>30 mm Platelet alumina</td>
<td>6 vol% Acrysol</td>
<td>36%</td>
</tr>
<tr>
<td>&lt;53mm Spraydried alumina (with fines)</td>
<td>6 vol% Acrysol</td>
<td>58%</td>
</tr>
</tbody>
</table>

A proprietary infiltration method has been developed within the MIT Three Dimensional Printing project for both metal and glass components. Details of this method have been omitted to protect intellectual property.

6.2.2 Test Results

Figures 6.3 - 6.10 are optical and SEM photos of infiltrated components showing completeness of the infiltration. Dark areas are the printed alumina particles and the light gray material surrounding them is the glass infiltrant. The defect shown in figure ??? is most likely attributed to pullout of an alumina particle during grinding.
Figure 6.3 3DPrinted test component infiltrated with glass-ceramic. Note small bridge across top is only 0.016" thick.

Figure 6.4: Close up view of infiltrated 30 micron platelet alumina component infiltrated with glass-ceramic.

Figure 6.5 Close up of section shown above.
Figure 6.6 Spherical spraydried alumina infiltrated with glass-ceramic

Figure 6.7 Close-up of spherical spraydried alumina infiltrated with glass ceramic. Defect is a result of grinding.
Figure 6.7 Close-up of spherical spraydried alumina infiltrated with glass ceramic. Defect is a result of grinding.

Figure 6.8 Fully dense complex component fabricated of spherical alumina and infiltrated with glass ceramic (1.5x1.5x1.0 inches).

6.2.2.1 Dimensional Change During Postprocessing

One of the greatest obstacles for the 3DP structural ceramics effort is controlling dimensional accuracy. Early experiments using spray dried alumina powder (<53 mm) showed dimensional changes of >30% linear in x, y, and z dimensions during firing from
green density to ~60% dense. Although, results were highly repeatable, this shrinkage exacerbates the problem of fabricating highly accurate components. In contrast, recent results show spherical and platelet alumina shrink 2% or less from the green state to the **fully dense** state via infiltration. This represents the first time complex 3DP components have been created which exhibit high strength and low shrinkage. Future work in this area will produce MOR data for infiltrated 3DP alumina-glass bodies and better statistical data on shrinkage.

Table 6.1: Shrinkage Values for 3DP Printed, Sintered, and Infiltrated Parts

<table>
<thead>
<tr>
<th></th>
<th>Coarse 30 micron</th>
<th>Spherical 30 micron</th>
<th>Spraydried</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Printed</td>
<td>Fired</td>
<td>Infiltrated</td>
</tr>
<tr>
<td>1</td>
<td>1.48</td>
<td>1.38</td>
<td>1.37</td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
<td>1.38</td>
<td>1.39</td>
</tr>
<tr>
<td>3</td>
<td>1.41</td>
<td>1.39</td>
<td>1.38</td>
</tr>
<tr>
<td>4</td>
<td>1.41</td>
<td>1.39</td>
<td>1.38</td>
</tr>
<tr>
<td>5</td>
<td>1.4</td>
<td>1.38</td>
<td>1.38</td>
</tr>
<tr>
<td>6</td>
<td>1.41</td>
<td>1.39</td>
<td>1.38</td>
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<tr>
<td>7</td>
<td>1.4</td>
<td>1.38</td>
<td>1.38</td>
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<tr>
<td>8</td>
<td>1.4</td>
<td>1.38</td>
<td>1.38</td>
</tr>
<tr>
<td>9</td>
<td>1.41</td>
<td>1.39</td>
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</tr>
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<td>10</td>
<td>1.41</td>
<td>1.39</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.4</td>
<td>1.39</td>
<td></td>
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<td>12</td>
<td>1.4</td>
<td>1.39</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1.4</td>
<td>1.39</td>
<td></td>
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<tr>
<td>14</td>
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<td>15</td>
<td>1.41</td>
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<td>16</td>
<td>1.41</td>
<td>1.39</td>
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<td>1.41</td>
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<td>18</td>
<td>1.41</td>
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<tr>
<td>19</td>
<td>1.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>1.41</td>
<td>1.39</td>
<td>1.38</td>
</tr>
</tbody>
</table>
Table 6.1: Shrinkage Values for 3DP Printed, Sintered, and Infiltrated Parts
Note: all measurements in inches

<table>
<thead>
<tr>
<th></th>
<th>Coarse 30 micron</th>
<th>Spherical 30 micron</th>
<th>Spraydried</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Printed</td>
<td>Fired</td>
<td>Infiltrated</td>
</tr>
<tr>
<td>% Change</td>
<td>1.74%</td>
<td>0.27%</td>
<td></td>
</tr>
<tr>
<td>Total Change</td>
<td>2.01%</td>
<td></td>
<td>1.23%</td>
</tr>
</tbody>
</table>

6.2.2.2 Density

Mercury porosimetry results indicate that five infiltrated bars ranged between 93% and 99% dense. This result is quite satisfying considering the samples were infiltrated in air and atmospheric pressure with no process optimization. It is noted that components that have an excess of infiltrant present exhibit a glassy layer on the exterior of the preform, which is fully dense. This encapsulating effect could be of use to future applications such as implantable housings, electronic packaging and other devices requiring a hermetic seal around a complex component or assembly.

6.2.2.3 Strength

Strength infiltrated spherical-alumina bars was assessed by 4 point bending standard procedure C1161-90. Samples of test bars printed aligned to the slow axis and the fast axis were tested for MOR. Bomas Machine Co. ground the samples to ASTM standard shape A (25.4mm x 2 mm x 1.5 mm with 45° chamfered edges). Results from these samples are shown below.

Table 6.2 Four Point Bending Strength of Infiltrated Spherical-Alumina Bars

<table>
<thead>
<tr>
<th>MOR (MPa)</th>
<th>Material</th>
<th>Density</th>
<th>Volume %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Axis</td>
<td>Fast Axis</td>
<td>Inceram</td>
<td>3.58 g/cc</td>
</tr>
<tr>
<td>201.8</td>
<td>201.9</td>
<td>Al₂O₃</td>
<td>3.70 g/cc</td>
</tr>
<tr>
<td>229.8</td>
<td>213</td>
<td></td>
<td></td>
</tr>
<tr>
<td>188.2</td>
<td>183.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2.2.4 Thermal Conductivity

Obtaining material property information for the glass infiltrated alumina is important for assessing its value in elevated temperature applications. Thermal conductivity data was obtained by determining its thermal diffusivity and then back calculating. Dr. D. Hasselman of Virginia Tech performed a laser pulse thermal diffusivity test on a 0.5" D x 0.065" sample returning a value of 0.027 cm²/s. No control sample was tested however.

The Laser pulse thermal diffusivity test functions by insulating a thin sample on the sides, inputting a metered amount of energy, and measuring the temperature rise on the back side immediately after exposure (to avoid cooling effects). Thermal diffusivity is then calculated by one of two methods:

\[
\alpha = \frac{0.48L^2}{\pi^2t_{1/2}}
\]

\[
\alpha = \frac{0.139L^2}{t_{1/2}}
\]

where L is sample thickness, \(t_{1/2}\) is time to 0.5 of maximum temperature rise, and it is the time axis intercept of the linear extrapolation of the heat rise curve.

The value of \(a\) from the literature for 99.5% Al₂O₃ at 300 K is approximately 0.075 cm²/s and a thermal conductivity of 35.6 W/m°K. From this it is can be
calculated that the infiltrated sample exhibits a conductivity of approximately 12.8 W/m°K assuming the same \( \rho C_p \) as alumina. Cordierite and Aluminum Titanate, common heat exchanger materials, have thermal conductivities of 3 and 1 W/m°K respectively.

6.2.2.5 Hermeticity

The heat exchanger application demands that intake gasses are not fouled by mixing with exhaust gasses. To demonstrate that infiltrated 3DP components can be hermetic, a component was fabricated for testing via helium infiltration. A hollow cylinder and a flat lid were printed, fired, and infiltrated with the Inceram glass-ceramic.

![Image](image.png)

Figure 6.9

Then, in a second infiltration run, the lid was sealed over the open end of the cylinder, making a closed cavity. The package was tested by Associated Testing, Burlington, MA to MIL-STD-750 Method 1071 Condition H pressurize to 30psi helium 2 hours.

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After pressurization the sample is removed to a vacuum chamber where a mass spectrometer "sniffs" for helium leaking back out of the package. If no helium is detected then the package is hermetic.

The test showed that the component was hermetic. Figure 6.10 is a schematic of the hermeticity test. This result is important not only for the heat exchanger application, but also valves, fittings, implantable devices, electronic packages, and many more. Ability to fuse two or more discrete 3DP components together to make a monolithic assembly via infiltration is also an interesting result.

Tests regarding the mechanical strength of bonds between fused structures, ability of infiltrant to wick through several discrete preforms to form a large monolith are areas for future research.

6.2.3 In-Ceram Glass Ceramic

The Vita In-Ceram process is used for the fabrication of ceramic dental prostheses by infiltrating an alumina skeleton with borosilicate glass. Table 6.3 shows the composition of the In-Ceram glass.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>(mol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>31</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>23</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>17</td>
</tr>
<tr>
<td>La₂O₃</td>
<td>13</td>
</tr>
<tr>
<td>TiO₂</td>
<td>7</td>
</tr>
<tr>
<td>CaO</td>
<td>5</td>
</tr>
<tr>
<td>CeO₂</td>
<td>3</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1</td>
</tr>
</tbody>
</table>

In-Ceram glass is noted for its excellent strength and low shrinkage. Flexural strength of In-Ceram was reported by Levy to be 600 MPa (3pt bending), and fracture toughness

Levy. H., "Working with the In-Ceram Porcelain System" Prostheses Dent. 44-45. 1-11
as a function of volume percent alumina is shown in Table 6.4. For comparison, Coors 99.5% alumina has a flexural strength of 379 MPa (3pt bending) and a fracture toughness of 4-5 MPa m$^{1/2}$.

<table>
<thead>
<tr>
<th>Fraction alumina (vol%)</th>
<th>Fracture toughness $K_c$ (MPa m$^{1/2}$)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.62</td>
<td>3.8±0.1</td>
</tr>
<tr>
<td>0.64</td>
<td>4.0±0.5</td>
</tr>
<tr>
<td>0.7</td>
<td>3.7±0.5</td>
</tr>
<tr>
<td>0.72</td>
<td>3.8±0.1</td>
</tr>
</tbody>
</table>

Alumina used for these tests had an average particle size of ~3.0μm and was 99.8% pure. In each case a porous alumina preform is placed on a paste of In-Ceram powder in a platinum crucible and fired to 1100°C for 2 hours. Fracture toughness was assessed by Wolf using the chevron-notch test on specimens 8mm in length and 4mm in diameter. The slot chord angle was 56 degrees. The test was conducted by measuring load line displacement as a function of applied load. Fracture toughness $K_{IC}$ is calculated by

$$K_{IC} = 24\frac{F_{max}}{D^{3/2}}$$

where $F_{max}$ is the maximum load and D the sample diameter.

### 6.2.4 Future 3DP Glass- Ceramic Research

Unfortunately, the In-Ceram glass-ceramic is extremely expensive ($8/g) making it unsuitable for most engineering applications. Developing a low cost glass-ceramic system having the desired mechanical and infiltration properties will be a component of future work in the 3DP-Structural Ceramics effort.

(1990)

Mechanical properties of most glass-ceramics make them appropriate for a multitude of structural ceramic applications. Table 6.5 indicates the relative performance of Glass-ceramics and other materials.

Table 6.5: Modulus of Rupture Values for Glass-Ceramics and Other Materials

(values for 0.5cm diameter rods in 3pt. bending)

<table>
<thead>
<tr>
<th>Material</th>
<th>Range of Values</th>
<th>Range of Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glasses</td>
<td>55-70</td>
<td>8000-10000</td>
</tr>
<tr>
<td>Glass-Ceramics</td>
<td>70-350</td>
<td>10000-50000</td>
</tr>
<tr>
<td>Electrical Porcelain (glazed)</td>
<td>80-140</td>
<td>12000-20000</td>
</tr>
<tr>
<td>High alumina (95% Al₂O₃)</td>
<td>200-350</td>
<td>30000-50000</td>
</tr>
</tbody>
</table>


Thermal properties of glass-ceramics are also highly attractive for many applications. Of primary interest is the ability to tailor thermal coefficient of expansion to meet a given application. Table 6.6 highlights thermal expansion characteristics of a few glass-ceramic compositions.

Table 6.6: Expansion Coefficients of Crystal Types which may be present in Glass-Ceramics (abbreviated)

<table>
<thead>
<tr>
<th>Crystal Phase</th>
<th>Thermal expansion coeff. (1/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li₂O-Al₂O₃-SiO₂</td>
<td>-86x10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>(20-700 C)</td>
</tr>
<tr>
<td>Al₂O₃-TiO₂</td>
<td>-19x10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>(20-1000 C)</td>
</tr>
<tr>
<td>2MgO-2Al₂O₃-5SiO₂</td>
<td>26x10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>(25-700 C)</td>
</tr>
<tr>
<td>Li₂O-Al₂O₃-4SiO₂</td>
<td>9x10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>(20-1000 C)</td>
</tr>
</tbody>
</table>


Thermal expansion was not measured for the 3DP alumina-glass composite. As mentioned above, the inceram glass is of the Lanthanum-alumino-silicate family, which is similar in properties to the lithium-alumino-silicate above.
Multilayered IC packages are one of the most interesting applications of 3DP structural ceramics where CTE matching is important. 3DP's ability to print a complete three dimensional package with internal cooling and interconnects in a single operation is very attractive for next generation, multichip processors. Current MLC designs by IBM use 90% alumina 10% glass (Calcia, magnesia, alumina silicate) to control shrinkage during processing and match CTE with molybdenum vias.

Another area of the 3DP alumina/glass-ceramic infiltration process to be explored in future work is that of selective infiltration. Selective infiltration has the potential to make very interesting composite 3DP structures which exhibit both mechanical integrity and low density for applications such as hot gas filters. An example of this would be to print a porous 3DP filter and infiltrate the outer few mm of the component, greatly increasing its strength without disturbing the fine porosity of the interior.

6.2.5 Materials Summary

Once again, exciting progress has been made in creating fully dense 3DP structural ceramic components via glass infiltration. High strength, complex ceramic components are now possible, greatly widening the field of applications which can be addressed by 3DP. Future work will include optimizing infiltrant composition and processing parameters.
6.3 High Volume Printer

A 3D Printer with increased build volume has the potential to reach new markets in investment casting, rapid tooling, direct metal components, and advanced ceramics. Not only does a larger build volume allow larger components to be fabricated, but increases the maximum potential buildrate of a given printhead. The cost of a large build volume printer is proportionately lower than smaller machines, and is shown to be more than offset by the increased productivity.

6.3.1 New Markets for Large Volume 3DP (LV-3DP)

New markets for the LV-3DP include metal casting prototypes for the automotive industry, rapid tooling for multi-cavity injection molding / die casting, manufacture large high capacity heat exchangers, and components for the petrochemical industry. Naturally the LV-3DP system would be able to produce current applications at a higher rate, lowering unit manufacturing cost of these components.

Casting Prototypes- Ford Motor Company has developed the Stratiform-Machining process for "rapid" prototyping large metal components such as engine blocks, cylinder heads, and transmission housings. Current methods require 20-24 weeks and can cost upwards of $250,000 per testable prototype. The Stratiform process reduces this to approximately 100 days and costs roughly $25,000 per working prototype. An added benefit of reduced cost and development time is the ability to iterate towards an optimum design. 3DP could compete directly with this methodology and deliver components in ever less time. Take for example an engine block that fits into a work volume of 24x24x24 inches. To print this entire volume at the current build rate quoted by Soligen (800 cc/hr) would take approximately 12 days. This would give a near net preform in, perhaps, alumina which could then be pressure infiltrated with aluminum. After any necessary heat treatment cycles, the component would be finish machined.

Table ??? below give a conservative breakdown of processes an their times.

<table>
<thead>
<tr>
<th>Table 6.7 Rapid Metal Prototyping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
</tr>
<tr>
<td>3D Print preform</td>
</tr>
</tbody>
</table>

137
Pressure Infiltrate 2 days  
Heat Treat 2 days  
Finish Machine 7 days  
Total 18 days

Even if this assessment were off by a factor of 3, this would be nearly 6 weeks faster than the Strati-form process. Disadvantages are design corrections to account for lower surface quality (must undersize bore of cylinders and bearing surfaces so finish machining has adequate material to remove), and stainless steel-bronze composite has considerably different material characteristics than either cast iron or aluminum (standard IC engine materials).

6.3.2 Increased Build-rate

Build rate is a function of both mechanical and electronic elements both returning to limitations in the fundamental physics of the printing operation. The basic elements of the printing process are, generation of control signals from the electronics, generation of droplets, and the chemical interaction of the binder droplet in the powder bed to form a primitive. Although bottle necks arise in each of these areas as print resolution and print speed are to increase, this section will concentrate printing operation and physical layout of the printer.

Printing operation - To achieve the maximum throughput for a given fast axis / printhead combination, the powderbed must have as many components per layer as possible. This is supported by the concept of "chip-to-chip" time in NC machining. The only time a NC machine tool is doing something useful, is when the bit is in contact with the work. Analogous to this in the 3D Printer is the time when binder is being applied to the powder. All other operations are merely overhead and should be reduced as much as possible.

Increasing the number of jets from 8 to 64 will have a substantial impact on buildrate. Beyond this, however, the costs of increasing the number of jets can no longer be justified by the decreasing build rate gains. As the number of jets increases, non-printing operations begin to dominate the total time per layer, eventually limiting the maximum buildrate achievable with a given printhead.
In the current Alpha configuration, the portion of the printing cycle allocated to spreading and diagnostics averages roughly 45 seconds per layer. Obviously to minimize the fraction of the total cycle this is to represent, the printer should print the entire width of the powderbed. In the case of manufacturing small components on a production 3DP Manufacturing system, the entire work volume of the powder bed should be printed, and then removed as a unit for part retrieval and cleanup.

Suggestions for reducing non printing delays in the design of a next generation printer are:

- Incorporate two spreader rollers into the fast axis carriage: Spreading and printing can be carried out simultaneously if the cycle is arranged appropriately. This would require that the printing and spreading begin on alternating ends of the fast axis after every layer. See figure ??? for the schematic of a proposed solution. This minimizes the overall travel of the slow axis, and the number of passes necessary.
The figure above shows a spreader roller on either side of the fast axis (shown without supports, printhead, drivegear, or umbilical). The smaller cylinders are the ceramic vibration transducers similar to those found on the MIT Alpha machine. The rocker above the fast axis actuates the rollers which are on floating gimbals ala Boeing 747 main landing gear. The new print cycle is as follows:

1. **Spread Powder**
2. **Print Layer**
3. **Repeat Cycle**
4. **Drop Piston**

**NOTE:** Fast axis is into page

- **Removable powder-bed** - This is key for printers with a shallow print-bed (small z-dimension) where the overall print cycle is proportionately shorter. As soon as the last layer is printed the printing technician or automatic tool changer removes the fully printed powder-bed and an replaces it with a clean, empty piston. Printing resumes immediately. The printed piston can now be taken to post processing for part extraction or, if the piston
is ceramic, placed directly in a furnace for binder burnout. This improvement does not
inherently change the architecture of current 3D Printers (the Alpha already has
accommodations for easily removing the piston from the front.

The illustration above is a multiprintbed 3DP Manufacturing Cell concept with automated
printbed removal and transport. The rotary in the center cantelevers three fast/slow axis arms
which simultaneously print on three powderbeds. The other three powderbeds are taken to
postprocessing areas during printing and are returned by the end of the print cycle. The rotary
then indexes one station to the right or left and printing commences immediately. This cycle is
intended to reduce delay between printruns for continuous production.

This system definitely represents a great leap from the current 3D Printers, with a host of
technical difficulties not addressed here. It does illustrate, however, how the concepts of the
flexible manufacturing cell can be applied to 3DP.

- On the fly jet correction - Although much more technically challenging than other
improvements, this would directly affect the overall accuracy and robustness of the process.

The current Alpha process cycle includes a pause of nearly 2 minutes every ten minutes for
assessing the conditions of the jets. Obviously this adds considerably to the total time
budget for the print cycle.
The diagram above shows a small camera on a positionable mount at the end of the fast axis stroke, which traverses the powderbed with the fast axis. During each spreading cycle 2 jets are checked for alignment, thereby assessing all eight jets (in the case of the Alpha printhead), every 4 layers.

- Increase Printbed Size- Increasing the size of the printbed has considerable effect on print rate, because it increases the printing fraction of the print cycle budget. Increasing the length of the fast axis has the greatest effect on build rate, but is also the more costly option. A more detailed cost analysis is necessary to determine the most practical fast axis length.

- Slow axis length can be increased at a relatively low cost and have substantial impact on build rate. Naturally this assumes that the previous suggestion of printing the entire print bed is adopted (in 3DP manufacturing). Figure 6.15 below indicates build rates calculated for slow axes lengths of 2, 10, 20, and 30cm versus interlayer delay (spreading and diagnostics). At the current 45 second / layer delay, printing a bed 30 cm wide (vs. 15.2) increases build rate by approximately 30%.
6.3.3 Conclusions

There are several relatively inexpensive mechanical improvements which can be made in future iterations of the current 3DP printers that have a large impact on build rate. While not the only or necessarily most immediate need to all applications 3DP, increasing build rate is very important for 3DP to ever become a viable manufacturing process of large and or high volume components. The suggestions made here address possible, and by no means, the only solutions for achieving higher 3DP productivity.

6.4 3DP Interactive Design Guide

An interesting secondary use of the evaluation software (in a more refined, interactive form) would be for educating designers of the strengths and limitations of 3DP. They could explore how Direct Shell Production, Rapid Tooling, or Rapid Manufacturing can solve their design problems. They will have the most up to date and accurate information on their application to enter into the database for comparison, assuring the quality of the results. Once educated, designers will be more likely to consider a free form fabrication method for their application. Secondly, and perhaps more intriguing, if 3DP falls short of their needs in some area, they will be
more likely to suggest improvements to the 3DP process or post processing methods so that they can exploit 3DP's numerous advantages.

Draper Labs has expressed some interest in the Quality Loss software as a marketable product not only for 3DP but any manufacturing process. Every manufacturing system has certain well defined limitations which can be incorporated in the database for comparison with a customer's needs. Reducing the time and expertise necessary to selecting the proper equipment for an application is potentially very valuable.
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APPENDIX A

Definitions and equations for fields in the Application Survey database.

There are five primary Lotus Approach data field types used in the 3DP Application Database: text, numeric, variable, calculated, and picture plus. Text fields are for information such as descriptions, names, and titles. Numeric, as the name implies, is for numeric data such as strength, weight, etc. Variable fields, somewhat of a misleading name, are fields that remain constant for all entries in the database. For example, fields for 3DP engineering characteristics were specified as variable fields so that they remain constant for each entry. Calculated fields are functions which carry out an operation and return a value. The calculated field bedsize multiplies the x, y, and z dimensions of the powderbed and returns the total volume of the powderbed. Picture Plus is a special field in Approach which allows one to import figures and graphics. This is the type of field used to show examples of the suggested applications.

Below is a list of the various fields which appear in the database accompanied by a brief description and the associated equation if applicable. The field definitions are grouped by function in the context of the Application Survey in the following categories: Quality Loss Fields, Printing Related Fields, 3DP Process Fields, Economic Fields, Material Fields, and Others.

Unfortunately the syntax for the Approach functions is rather unattractive and difficult to decipher. The code below is, however, as it appears in Approach to preserve its format.
NOTE: The syntax for raising a variable to a power appears as: \( x^y = \text{pow}(x, y) \). Likewise, if statements appear as if\((x, y, z) = \text{if } x \text{ is true, then } y, \text{ else } z \). This makes for some very disgusting looking code.

Quality Loss Fields-

1. **sizeloss** - Calculates loss based on the size of the component when compared to the maximum piston size of the printer.

   - \( \text{Pow}(\text{PARTSIZE} / \text{bedsize}, 2) \)

2. **tolerloss** - Calculates the loss based on the tolerances 3DP is capable of keeping compared with those of the traditional method for fabricating the given application.

   - \( \text{If}(\text{PRODUCTS.PLUSDIM} > 0 \text{ and } \text{PRODUCTS.MINDIM} > 0, \text{Pow}(\text{3dpACC} - (\text{PRODUCTS.DIMACCURCY}), 2) / \text{Pow}(\text{PRODUCTS.PLUSDIM} + \text{PRODUCTS.MINDIM}), 2), \text{If}(\text{PRODUCTS.PLUSDIM} = 0, \text{If}(\text{PRODUCTS.DIMACCURCY} > 3\text{dpACC}, 0, \text{Pow}(\text{3dpACC} - (\text{PRODUCTS.DIMACCURCY}), 2) / \text{Pow}(\text{PRODUCTS.PLUSDIM} + \text{PRODUCTS.MINDIM}), 2)), \text{If}(\text{PRODUCTS.DIMACCURCY} < 3\text{dpACC}, 0, \text{Pow}(3\text{dpACC} - (\text{PRODUCTS.DIMACCURCY}), 2) / \text{Pow}(\text{PRODUCTS.PLUSDIM} + \text{PRODUCTS.MINDIM}), 2)))) \)

3. **prodloss** - Calculates the loss associated with the difference in the minimum annual production volume and that possible by a single 3DP machine.

   - \( \text{If}(\text{PRODUCTS.PLUSPROD} > 0 \text{ and } \text{MINPROD} > 0), \text{Pow}(\text{PRODUCTS.PROD_VOL} - (\text{TOTAL}), 2) / \text{Pow}(\text{PRODUCTS.PLUSPROD} + \text{MINPROD}), 2), \text{If}(\text{PRODUCTS.PLUSPROD} = 0, \text{If}(\text{TOTAL} > \text{PRODUCTS.PROD_VOL}, \text{Pow}(\text{PRODUCTS.PROD_VOL} / \text{TOTAL}, 2), \text{Pow}(\text{PRODUCTS.PROD_VOL} - (\text{TOTAL}), 2) / \text{Pow}(\text{PRODUCTS.PLUSPROD} + \text{MINPROD}), 2)), \text{If}(\text{TOTAL} < \text{PRODUCTS.PROD_VOL}, \text{Pow}(\text{TOTAL} / \text{PRODUCTS.PROD_VOL}, 2), \text{Pow}(\text{PRODUCTS.PROD_VOL} - (\text{TOTAL}), 2) / \text{Pow}(\text{PRODUCTS.PLUSPROD} + \text{MINPROD}), 2)))) \)

4. **surfloss** - Calculates the loss associated with the difference in surface quality of the current fabrication process and that of 3DP.

   - \( \text{If}(\text{PLUSSURF} > 0 \text{ and } \text{PRODUCTS.MINSURF} > 0), \text{Pow}(\text{PRODUCTS.SURFACE} - (\text{SURFQUAL}), 2) / \text{Pow}(\text{PLUSSURF} / 1000 + \)
PRODUCTS.MINSURF / 1000), 2), If(PLUSURF = 0, If(PRODUCTS.SURFACE > SURFQUAL, Pow(SURFQUAL / PRODUCTS.SURFACE, 2), Pow((PRODUCTS.SURFACE - (SURFQUAL), 2) / Pow((PLUSURF + PRODUCTS.MINURF), 2)), If(PRODUCTS.SURFACE < SURFQUAL, Pow(PRODUCTS.SURFACE / SURFQUAL, 2), Pow((PRODUCTS.SURFACE - (SURFQUAL), 2) / Pow((PLUSURF + PRODUCTS.MINURF), 2)))))

5. strenloss - Calculates the loss associated with the difference in 4 point MOR for the current material and the 3DP Alumina-Glass composite

- If((PLUSMOR > 0 and MINMOR > 0), Pow((MOR) - (3ptSTREN), 2) / Pow((PLUSMOR + MINMOR), 2), If(PLUSMOR = 0, If(MOR < 3ptSTREN, Pow(MOR / 3ptSTREN, 2), Pow((MOR) - (3ptSTREN), 2) / Pow((PLUSMOR + MINMOR), 2)), If(MOR > 3ptSTREN, Pow(3ptSTREN / MOR, 2), Pow((MOR) - (3ptSTREN), 2) / Pow((PLUSMOR + MINMOR), 2))))

6. denloss - Calculates the loss associated with the difference in component density possible with 3DP and that dictated by the application

- If((PRODUCTS.PLUSDEN > 0 and PRODUCTS.MINDEN > 0), Pow((DENSITY) - (PRODUCTS.PARTDENSE), 2) / Pow((PRODUCTS.PLUSDEN + PRODUCTS.MINDEN), 2), If(PRODUCTS.PLUSDEN = 0, If(PRODUCTS.PARTDENSE >= DENSITY, 0, Pow((DENSITY) - (PRODUCTS.PARTDENSE), 2) / Pow((PRODUCTS.PLUSDEN + PRODUCTS.MINDEN), 2)), If(COMPAKY1.GREENDEN <= DENSITY, 0, Pow((PRODUCTS.PARTDENSE) - (DENSITY), 2) / Pow((PRODUCTS.PLUSDEN + PRODUCTS.MINDEN), 2)))))

**Fields Associated with Printing**

1. layertime - Print time per layer - ((bedy / YSPEED) + delay)

2. layernumber - Number of layers in powder bed - bedz / LAYERTHICK

3. yspeed - Slow Axis Speed - NOZZLES * 0.04

4. partweight - Component weight - PARTSIZE * PRODUCTS.PARTDENSE / 100 * MATDENSE * (1 - PRODUCTS.VOIDVOL / 100)

5. unishour - Production rate - 1 / printtime

6. bedsize - Volume of Powderbed - bedx * bedy * bedz

7. bedx - Bed fast axis dimension

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8. **bedy** - Bed slow axis dimension

9. **bedz** - Bed z axis dimension

10. **total** - 3DP Production Volume per year - If(bedsize / PARTSIZE > 2, (HOURYEAR / (layernumber * ((bedy / YSPEED) + delay) / 3600)) * ((bedx / PRODUCTS.SIZEX) * (bedy / PRODUCTS.SIZEY) * (bedz / PRODUCTS.SIZEZ)), ((HOURYEAR / (layernumber * ((bedy / YSPEED) + delay) / 3600))))

11. **loss2** - Quality loss for prototype component - (sizeloss + tolerloss + surfloss + strenloss + denloss) / 6

12. **partsize** - Cubic volume which fully incloses component

   - PRODUCTS.SIZEX * PRODUCTS.SIZEY * PRODUCTS.SIZEZ

13. **sizex** - Component fast axis dimension

14. **sizey** - Component slow axis dimension

15. **sizez** - Component z axis dimension

16. **printtime** - Time to print entire powderbed  - PRODUCTS.SIZEZ / LAYERTHICK * ((PRODUCTS.SIZEY / (YSPEED * NOZZLES)) + delay) / 3600

17. **loss** - Quality Loss value for full production - (sizeloss + tolerloss + prodloss + surfloss + strenloss + denloss) / 6

18. **costproto** - Prototype component cost - (printtime * OPWAGE * OPSUPER / (100)) + (printtime * ANNOVER / HOURYEAR) + (ROUTOVER / OVERFREQ * printtime) + (PARTSIZE * (1 - PRODUCTS.VOIDVOL / 100) * BAD_FIELD_REFERENCE / 1000) + PRODUCTS.ADDCOST

19. **prodcost** - Production cost per part - Trunc(OPWAGE * HOURYEAR * OPSUPER / (PARTYEAR * 100) + ANNOVER / PARTYEAR + ROUTOVER * HOURYEAR / (OVERFREQ * PARTYEAR) + PARTSIZE * PRODUCTS.PARTDENSE / 100 * (1 - PRODUCTS.VOIDVOL / 100) * POWCOST / 1000 + PRODUCTS.ADDCOST / 0.01) * 0.01

---

**3DP Process Parameters (variable fields)**

1. **density** - Maximum component density after post processing  - 100%

2. **maxtemp** - Maximum useful temperature of 3DP structural component  - 500C

3. **machcost** - Cost of 3DPrinter - $200,000

4. **delay** - Spreading and Diagnostic delay - 45 sec
5. **bedx, bedy, bedz** - Powderbed dimensions - 30.5cm, 13.75cm, 30.5cm

6. **xspeed** - Fast axis traverse speed - 1.5 m/s

7. **layerthick** - Thickness of a single layer - 177microns

8. **nozzles** - Number of jets - 8

9. **4ptstren** - Modulus of Rupture for 3DP Alumina-Glass components - 200 MPa

10. **surfqual** - Average Ra Surface Roughness of printed components - 25 micron

11. **secondmatl** - Maximum percentage of secondary material which can be printed - 40%

12. **geom** - Geometry category possible with 3DP - 5

**Economic Variables -**

1. **opwage** - operator wage per hour

2. **lendrate** - lending rate for capitol borrowed to purchase equipment

3. **taxrate** - current taxation for company

4. **routover** - routine overhaul costs associated with machine maintenance.

5. **lendyear** - years of financial note on equipment

6. **optrain** - costs associated with operator training

7. **overfreq** - routine overhaul frequency (hours)

8. **sparepart** - spare parts purchased at the outset for machine upkeep

9. **opsuper** - percentage of operating time that the operator must be present

10. **annover** - annual overhaul costs

11. **depyear** - number of years for depreciation

12. **houryear** - number of working hours per year (2000)

13. **deprec** - deprecation rate on capital equipment

14. **salvage** - salvage value of machine after useful life - MACHCOST * 0.1

15. **taxred** - tax reduction based on depreciation of capital equipment -

   (MACHCOST * (1 - DEPREC / 100) / LENDYEAR) * TAXRATE / 100
16. \textit{cf0} - initial cashflow for equipment purchase and training - \((-\text{MACHCOST} - \text{SPARPART} - \text{OPT?AIN})\)

17. \textit{cf14} - yearly cashflow from revenues and depreciation of capital equipment
\((\text{PRODUCTS.PARTVAL} - \text{COSTPART}) \* (1 / \text{printtime}) \* \text{HOURYEAR} + \text{taxred})\)

18. \textit{cflast} - cashflow in last year when salvage cost of equipment is added to revenues. \text{CF14 + SALVAGE}

19. \textit{prsworth} - present worth of investment in capital equipment (3DPrinter) for producing a certain application under the given financial and production related parameters. Trunc((\text{CF0} + \text{CF14} * ((\text{Pow}((1 + \text{LENDRATE} / 100), (\text{LENDYEAR} - 1)) - 1) / (\text{LENDRATE} / 100) * ((\text{Pow}((1 + \text{LENDRATE} / 100), (\text{LENDYEAR} - 1)))))) + \text{CFLAST} * (1 / \text{Pow}((1 + \text{LENDRATE} / 100), \text{LENDYEAR}))) / 1000) * 1000

\textbf{Material Related Variables - from Coors Ceramics Company}

1. \textit{powcost} - cost of ceramic powder - \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Silicon Nitride'}, 22, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Alumina'}, 88, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Silicon Carbide'}, 13, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'3DP Alumina-Glass'}, 140, 50))))

2. \textit{MOR} - Modulus of Rupture data (test ASTM F417-78) -
\text{If}(\text{PRODUCTS.MATERIAL} = \text{'Silicon Nitride'}, 600, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Alumina'}, 380, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Silicon Carbide'}, 460, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Aluminum Titanate'}, 25, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Cordierite'}, 120, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'3DP Alumina-Glass'}, 200, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'TTZ'}, 620, 100))))))

3. \textit{Youngsmod} - Elastic modulus (test ASTM C848-78) -
\text{If}(\text{PRODUCTS.MATERIAL} = \text{'Silicon Nitride'}, 300, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Alumina'}, 370, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Silicon Carbide'}, 340, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Aluminum Titanate'}, 5.5, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Cordierite'}, 83, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'3DP Alumina-Glass'}, \text{'Not Tested'}, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'TTZ'}, 200, 0))))))

4. \textit{Hardness} - (test Knoop 1000g) - \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Silicon Nitride'}, 14.7, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Alumina'}, 14.1, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Silicon Carbide'}, 24.5, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Aluminum Titanate'}, 1, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'Cordierite'}, 1, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'3DP Alumina-Glass'}, \text{'Not Tested'}, \text{If}(\text{PRODUCTS.MATERIAL} = \text{'TTZ'}, 300, 100)))))))
5. **Stiffness - Stiffness to weight ratio** - If(PRODUCTS.MATERIAL = 'Silicon Nitride', 94, If(PRODUCTS.MATERIAL = 'Alumina', 96, If(PRODUCTS.MATERIAL = 'Silicon Carbide', 127, If(PRODUCTS.MATERIAL = 'Aluminum Titanate', 2, If(PRODUCTS.MATERIAL = 'Cordierite', 36, If(PRODUCTS.MATERIAL = '3DP Alumina-Glass', 'Not tested', If(PRODUCTS.MATERIAL = 'TTZ', 35, 0))))))))

6. **Thermoshock - thermal shock resistance** - (test quenching in water from elevated temperature) - If(PRODUCTS.MATERIAL = 'Silicon Nitride', 94, If(PRODUCTS.MATERIAL = 'Alumina', 96, If(PRODUCTS.MATERIAL = 'Silicon Carbide', 127, If(PRODUCTS.MATERIAL = 'Aluminum Titanate', 2, If(PRODUCTS.MATERIAL = 'Cordierite', 36, If(PRODUCTS.MATERIAL = '3DP Alumina-Glass', 'Not tested', If(PRODUCTS.MATERIAL = 'TTZ', 35, 0)))))))

7. **Matdense - density (test ASTM C20-83)** - If(PRODUCTS.MATERIAL = 'Silicon Nitride', 3.31, If(PRODUCTS.MATERIAL = 'Alumina', 3.89, If(PRODUCTS.MATERIAL = 'Silicon Carbide', 3.1, If(PRODUCTS.MATERIAL = 'Aluminum Titanate', 3.1, If(PRODUCTS.MATERIAL = 'Cordierite', 2.51, If(PRODUCTS.MATERIAL = '3DP Alumina-Glass', 3.5, If(PRODUCTS.MATERIAL = 'TTZ', 5.75, 0)))))))

8. **Fractures - fracture toughness (notched beam test)** - If(PRODUCTS.MATERIAL = 'Silicon Nitride', 6, If(PRODUCTS.MATERIAL = 'Alumina', 4, If(PRODUCTS.MATERIAL = 'Silicon Carbide', 4, If(PRODUCTS.MATERIAL = 'Aluminum Titanate', 1, If(PRODUCTS.MATERIAL = 'Cordierite', 1, If(PRODUCTS.MATERIAL = '3DP Alumina-Glass', 'not tested', If(PRODUCTS.MATERIAL = 'TTZ', 11, 0)))))))

9. **Thermcond - thermal conductivity (test ASTM C408-82)** - If(PRODUCTS.MATERIAL = 'Silicon Nitride', 15, If(PRODUCTS.MATERIAL = 'Alumina', 35, If(PRODUCTS.MATERIAL = 'Silicon Carbide', 125, If(PRODUCTS.MATERIAL = 'Aluminum Titanate', 1, If(PRODUCTS.MATERIAL = 'Cordierite', 3, If(PRODUCTS.MATERIAL = '3DP Alumina-Glass', 12, If(PRODUCTS.MATERIAL = 'TTZ', 2.2, 0)))))))

10. **Maxusetemp - maximum useful temperature** - If(PRODUCTS.MATERIAL = 'Silicon Nitride', 1200, If(PRODUCTS.MATERIAL = 'Alumina', 1750, If(PRODUCTS.MATERIAL = 'Silicon Carbide', 1400, If(PRODUCTS.MATERIAL = 'Aluminum Titanate', 1400, If(PRODUCTS.MATERIAL = 'Cordierite', 1, If(PRODUCTS.MATERIAL = '3DP Alumina-Glass', 600, If(PRODUCTS.MATERIAL = 'TTZ', 500, 0))))))))
11. *thermexpansion* - coefficient of thermal expansion (test ASTM C372-81) -
   \[
   \text{If}(\text{PRODUCTS.MATERIAL} = \{'\text{Silicon Nitride}'\}, 3, \\
   \text{If}(\text{PRODUCTS.MATERIAL} = \{'\text{Alumina}'\}, 8.2, \text{If}(\text{PRODUCTS.MATERIAL} = \\
   \{'\text{Silicon Carbide}'\}, 4.3, \text{If}(\text{PRODUCTS.MATERIAL} = \{'\text{Aluminum Titanate}'\}, 0.7, \\
   \text{If}(\text{PRODUCTS.MATERIAL} = \{'\text{Cordierite}'\}, 1.7, \text{If}(\text{PRODUCTS.MATERIAL} = \\
   \{'3DP Alumina-Glass'\}, \text{not tested}, \text{If}(\text{PRODUCTS.MATERIAL} = \{'\text{TTZ}'\}, \\
   10.1, 0))))))))
   \]

**Other Variables:**

1. *Part dense* - density of component
2. *addcost* - additional processing cost per component after printing
3. *voidvol* - percentage of total component work volume NOT printed. E.g., a thin tube truss only occupies 5-10% of the volume its maximum dimensions outline.
4. *partval* - Value of printed component
5. *usage* - Percentage of maximum printer capacity needed to fulfill printing requirements
6. *diecost* - cost of dies when comparing 3DP to injection molding
7. *size x, size y, size z* - dimensions of smallest volume in which the component will fit. \( x = \text{fast axis}, y = \text{slow axis}, z = \text{z-axis} \)
8. *variantvol* - Ratio of product variants in production run (e.g., lefthanded molds vs. right handed molds for a handle)
9. *All of the plus*** and min*** values are the tolerances on their namesake variables (mindim and plusdim are the dimensional tolerances)
10. *geometry* - geometry category
11. *varthick* - variable thickness section
12. *aspectrat* - aspect ratio of component
13. *describe* - prose description of component
14. *procname* - name of competing process for analysis
15. *process_id* - identification number of each process

155
16. *inunder* - internal undercuts (yes - no?) Used to disqualify other processes such as injection molding where cores cannot be removed from part if there are internal undercuts.

17. *undercut* - external undercuts (yes - no?)

18. *symm* - is the part axiosymmetric?

19. *comp_id* - application identification number

20. *prod_vol* - yearly production volume of component

21. *reference* - literature reference

22. *date* - date when applicatin record was last updated

23. *name* - application name

24. *localcomp* - location specific material composition

25. *surface* - surface quality - selected as a function of which manufacturing process is currently used to fabricate a component
APPENDIX B:

DETAILS ON OTHER APPLICATIONS OF 3DP
Application of 3DP - Back to the Future:
Mike Rynerson - February 7, 1994

Three Dimensional Printing has the potential to make a great impact in fields far removed from traditional engineering and manufacturing. This is made evident through interest expressed by people from architectural and artistic backgrounds, who have recognized how 3DP could ease and enhance the creative process. For them, 3DP would be an avenue to greater flexibility in expressing ideas in material. Traversing to the other extreme, there are those users who want to do the opposite, i.e., go from reality back to a representation of reality. One such area that has some very exciting possibilities is paleontology!

Widespread interest in paleontology, or the study of fossil remains, has received a renaissance in recent years due in large part to Michael Crichton's *Jurassic Park* and the following motion picture by Stephen Spielberg. This will undoubtedly have a direct impact on the amount of money made available by museums to researchers for expanded efforts in recovering fossils worldwide. But where does 3DP fit in?

One must first pull on the dust covered boots of the paleontologists for a moment, and think about how fossils are recovered. First a fossil rich area must be located where strata from the *Mesozoic* (225 - 65 million years ago) has neared the surface because of erosion or tectonic movements. Then the painfully slow process of hunt and peck begins, searching for the tell tail (excuse the pun) signs of fossil remains which might give away a treasure chest of bones hiding just below the surface. Unfortunately, this is only the beginning, because once located, the fossils must be exposed by hammering, picking and *brushing* away the stone that has so caringly protected the delicate fossils for millennia. This process goes on until the bones can be cataloged,
photographed, bagged, tagged and shipped back to a laboratory for further analysis and reassembly for display purposes. The entire process from "Oh look, a bone on the ground!" to "Oh look daddy, a pachycephalosaur!" can take many years of blood, sweat and tears.

To expedite locating fossil remains, recent developments have made possible a sort of "land sonar". Probes connected to a computer are placed underground opposite and some distance away from a small explosive charge. When the charge is detonated, shockwaves are transmitted through the material separating the probes and explosives. Fortunately for the scientists involved, different materials transmit shock waves at different speeds, a fact that is exploited to produce a computer image of the fossilized dino who happened to die between the probes. From here on out, however, it is the same game of dig up the bones. And if the fossils are buried too deeply, they might still go unrecovered simply because of prohibitive excavation costs.

3DP to the rescue! Instead of recovering the original fossils, at the expense of years of toil and funds, why not use detailed "sonar" images of the fossils to create 3D geometry files of the find and print a replica of the bone in ceramic? The process would now go something like this: Dr. Oldbones goes into the field with his/her team and picks a likely site for diapsid reptilian creatures of the Mesozoic period, drills a few holes and fires a few preliminary sonar "pings" to triangulate on the long dead prey. Then a second array of sensor wells is strategically drilled around the fossil bed, so as to create a highly accurate 3D image when less powerful shock waves are transmitted. Voila, The field work is complete! Now the 3D geometry file can be sent via modem / internet to colleagues at the home institution or anywhere in the world for that matter. There the file is scaled to printable proportions (no one would expect to print up an 8 foot long brachiosaurus femur with a huge 3DP machine), and recreated in ceramic for evaluation and display.

Advantages of this method are immediately obvious given that sensor technology will continue to improve, providing the necessary resolution for highly accurate representation of the fossil's features. Monetary and temporal costs would be greatly reduced as the countless hours of labor associated with the excavation and preparation of specimens are eliminated. Ecological damage, i.e., marring the landscape for excavations, would no longer be a factor in gaining admittance to areas where fossils are believed to exist. Lastly the speed at which information
could be shared between experts around the world would facilitate faster dissemination of fossil finds, ultimately helping us to better understand these most intriguing of creatures.

Imagine the possibilities: "Hello Janet, did you get that skull I e-mailed you?" "Hi Bob, it just came out of the printer." "Whadda you think, *archaeopteryx*?" "I'm not sure Bob, but I'd say you've got an *ornitholestes* there. Are you going to recover the original?" "Nah, it's 5500 feet down, I was tagging along with an oil drilling expedition . . ." 

3DP could be the future of the past.
Hybrid/Electric Automobile Systems - Potential for the application of the 3DP Technology

Introduction

"Two decades after the first energy crisis gripped America, gasoline prices are at an all-time low. The once-heavily funded government research programs in alternative engines, alternative fuels, and lightweight materials have been slowly dwindling away."

"Given the glut of crude oil, it might have been reasonable to expect these programs to vanish altogether. Instead, last fall President Clinton announced that the government's national defense and weapons laboratories and the domestic auto companies would collaborate on a massive effort to sharpen the competitiveness of the U.S. auto industry. The ambitious program is three pronged: Researching advanced manufacturing technology, investigating near-term improvements in automobile efficiency, safety, and

† Excerpt from Popular Science "Emerging Technologies for the Supercar", June 1994. p. 95
emissions, and lastly a ten year program to build a production-ready prototype of a car capable of 80 miles to a gallon."

"The exact approach (to achieving 80 mpg) is still being debated, but there is virtually universal agreement that the car would use some form of hybrid drive - a combination of fuel burning powerplant generating electricity, and a final electric drive. Some of the components that may appear in an automotive hybrid drive system already exist in military applications, including flywheel storage units on communications satellites: drive motors developed for submarines and torpedoes; even a cruise missile gas turbine."

"A hybrid has three fundamental systems. The first, the primary power source, is either an engine-driven generator or alternative such as a fuel cell. The second requirement is a power storage unit, which might be a conventional battery or a more exotic solution such as an energy-storing flywheel or an ultracapacitor. The final link in hybrid drivetrains is a motor, almost always an electric motor capable of acting as a generator as well."

Figure 2 shows some of the variations of a hybrid automotive power system. In each frame the three subsystems mentioned above are present: power production, storage,
and conversion. Components for each system must have exceptional mechanical and or electrical properties to stand up to the severe loads anticipated in normal operation. This will force designers to look to advanced materials and manufacturing processes to achieve the necessary component characteristics.

The Role of Three Dimensional Printing (3DP)- The initial goal of the "New Generation Vehicle" project set forth by President Clinton calls for the development of a production ready prototype of an automobile which can achieve 80 miles per gallon. In the attempt to reduce weight and maximize structural integrity of nearly every component in the power-train and chassis, designers will need the utmost in manufacturing flexibility. This is the forêt of Three Dimensional Printing.

3DP Power Plant Components - Options for power generation in hybrid vehicles include advanced 4-stroke spark-ignition engines, 2-stroke spark-ignition engines, diesel engines, advanced automotive gas turbines, and fuel cells. Each of these systems can benefit from the use of advanced ceramic components produced via the 3DP process.

Components such as valves, valve guides, piston caps, exhaust port liners, and tappets in piston engines are known to benefit from substitution of ceramic components for the traditional metal components. Gas turbines have been developed with ceramic components such as rotors, vanes, exhaust baffling, and scroll, which provide higher efficiency, lower mass and increased performance density. Fuel cells operating at extreme temperatures require the exceptional high temperature stability of advanced ceramics.

3DP Energy Storage Components - Electrical energy in hybrid cars is to be stored in batteries, flywheels, ultracapacitors, or a combination of these devices. Components for advanced batteries using very corrosive substances such as the sodium acid battery will call for internal components resistant to this environment. Flywheels are under amazing mechanical stress by the very nature of their operation necessitating bearing, structural, and failure containment components of the highest integrity†.

3DP Energy Conversion Components - Energy conversion is usually performed by an electric motor which converts the stored electrical energy into mechanical energy to

† Advanced ceramics can be used for bearings, and flywheel burst containment armor.
propel the car, and from mechanical braking energy to rotational energy of the flywheel. Ceramic rotors and bearings could be specified for advanced electric motors which give optimum electrical and mechanical performance.

**3DP Advantage** - Production prototypes of these components can be developed much more quickly with the 3DP process. Because 3DP allows designers to go directly from CAD files to a highly complex ceramic (or metal) prototype, development time and expense would be slashed. 3DP’s ability to create components of arbitrary geometry and a variety of materials gives designers the freedom to optimize concepts for performance and manufacturability.

![3D PDM Model](image)

**Figure 3:** Example of Complex Ceramic Turbine Components which could be fabricated using the 3DP process

Whether it be in creating casting molds for superalloy flywheel components or monolithic silicon nitride valves for an advanced internal combustion engine, the Three
Dimensional Printing process will shorten the path to making ultra-efficient hybrid-electric vehicles a reality.
APPENDIX C
VIEWS OF ANALYSIS SPREADSHEET
# Product: CCHX for Furnace Applications

## Product Characteristics:

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<th>Material Attribute</th>
<th>Target</th>
<th>Tolerance</th>
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<tbody>
<tr>
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<td>Geometry Category</td>
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<tr>
<td>Surface Roughness</td>
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<td>Dimensional Accuracy</td>
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<td>Limit</td>
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<td>MPa</td>
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<tr>
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<td>Value</td>
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## Process Capabilities:

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<thead>
<tr>
<th>Process Capability</th>
<th>LPM</th>
<th>3DP</th>
<th>Slip Casting</th>
</tr>
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<tbody>
<tr>
<td>Max Size</td>
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<td>2500</td>
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<tr>
<td>Min Size</td>
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<td>6.00</td>
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<td>Surface Roughness</td>
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<td>Dimensional Accuracy</td>
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## Print Rate Calculations

Mike Ryanson
5/5/94

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<th>Part Dimensions</th>
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<tr>
<td>Y size</td>
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<td>12.01</td>
</tr>
<tr>
<td>Z size</td>
<td>36.5</td>
<td>12.01</td>
</tr>
</tbody>
</table>

| Spread & Diagnostic Delay (s) | 45 | 45 |
| Fast Auto Spread units (in)   | 140 | 36.37 |
| Slow Auto Spread units (inches) | 0.84 | 0.02 |
| Layer Thickness at (g)        | 8.0177 | 0.0070 |
| Number of sections            | 3  | 2  |

Print time (h) = 67.16
# CCHX for Furnace Applications

## Return on Investment Calculation

User enters only **BOLD** text values, normal values filled automatically

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<thead>
<tr>
<th></th>
<th>3DP</th>
<th>Slip Casting</th>
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<tbody>
<tr>
<td>Operator Hourly wage</td>
<td>25</td>
<td>25</td>
<td>25</td>
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<tr>
<td>% Direct Operator Supervision</td>
<td>25%</td>
<td>50%</td>
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<tr>
<td>Annual overhaul costs</td>
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<td>Routine overhaul costs</td>
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<tr>
<td>Total working hours / year</td>
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<td>2000</td>
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<tr>
<td>Routine overhaul frequency (h)</td>
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<td>Spare Parts</td>
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<td>Salvage value</td>
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<td><strong>Cost per part</strong></td>
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<td><strong>600.44</strong></td>
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<td><strong>Capital recovery term (yrs.)</strong></td>
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## Comments:

- **DIV/OI**
- Part Too Large for LPM
## Financing Variables

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<td>Years of term (N)</td>
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