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DEVELOPMENT OF ADVANCED CERAMIC MANUFACTURING TECHNOLOGY

FINAL REPORT

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TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

Due to their high temperature capability, low density, high stiffness, and corrosion resistance, advanced structural ceramics are enabling materials for new transportation engine systems that have the potential for significantly reducing energy consumption and pollution in automobiles and heavy vehicles. Currently, ceramics are used in limited production applications for cam rollers and injector plungers, and in the form of coatings applied to cylinder head fire decks and pistons. In the early 1980's the U.S. Department of Energy (DOE) Office of Transportation Technologies (OTT) and U.S. industry accelerated activity in the development of ceramics for advanced heat engines. DOE's Ceramic Technology Project (CTP) at Oak Ridge National Laboratory (ORNL) was a major program that demonstrated the performance and reliability of advanced ceramics for heat engines including automotive gas turbine and heavy-duty diesel engines. In a major CTP program initiative, Norton Company's Northboro R&D Center (now a division of Saint-Gobain Industrial Ceramics, Inc.) successfully completed an Advanced Processing contract demonstrating reliable and high-tensile-strength ceramics. The Processing program approach was to implement in-process inspection, nondestructive evaluation, statistical process control, mechanical characterization, and proof testing in the production of tensile specimens by both injection molding and pressure slip casting. Utilizing a new closed-loop aqueous process and systematic flaw reduction methodologies, the program achieved 1 GPa tensile strengths and high Weibull modulus in high temperature silicon nitride, thereby demonstrating that advanced ceramics can be viable propulsion system materials.

In a parallel effort to the CTP, the DOE Advanced Turbine Technology Applications Program (ATTAP) continued the development of automotive gas turbine systems and several ceramic components were incorporated as enabling materials. The ATTAP led to further advancements in ceramic processing technology, and demonstrated ceramic engine component performance advantages. Norton/TRW Ceramics (NTC) a joint venture between Norton Company and TRW established in 1985 to develop ceramic engine components, was a major ceramic component supplier to two ATTAP teams.

With advanced ceramic component reliability demonstrated in the CTP, DOE and industry attempted to address manufacturing cost barriers. Realizing that the successful commercialization of advanced ceramics depended on a significant reduction in manufacturing costs without the compromise of reliability, the Cost Effective Ceramics (CEC) effort was initiated under CTP in 1993. NTC and other ceramic suppliers participated in studies for CTP that analyzed the major cost factors in ceramic engine component manufacturing unit operations. These included machining, inspection, raw material, forming, and densification.

In 1993, at the start of the CEC program, the Norton/TRW joint venture became a wholly owned subsidiary of SGIC and part of Norton Advanced Ceramics

(NAC) Division. Shortly thereafter, NAC was selected to lead one of three major Advanced Ceramic Manufacturing Technology (ACMT) Program Teams that became the backbone of the Cost-Effective Ceramics initiative. The ACMT Program involved manufacturing demonstrations of selected ceramic components, and addressed the major elements of cost modeling, densification, ceramic machining, powder processing, in-process controls, intelligent processing, testing, and performance acceptance.

The overall objectives of NAC's ACMT Program were to design, develop, and demonstrate advanced manufacturing technology for the production of ceramic exhaust valves for diesel engines. The specific objectives were: (1) to reduce the manufacturing cost by an order of magnitude; (2) to develop and demonstrate process capability and reproducibility; and (3) to validate ceramic valve performance, durability, and reliability in fixture rig and engine testing.

In order to achieve these targeted objectives, a multi-disciplinary team was assembled to bring together the required technology. Collectively, this team included professionals with a broad base of experience in ceramic component development and manufacturing and in engine design and testing.

- **NAC** was the ceramic component manufacturer and program leader.
- **Detroit Diesel Corporation (DDC)**, a major diesel engine builder, was responsible for component design, inspection, and testing.
- **SGIC's Northboro R&D Center (NRDC),** a corporate ceramics research division, was responsible for ceramic process development and intelligent process control.
- **BDM Federal, Inc.** and **MATSYS, Inc.** were responsible for development of intelligent processing methods. When the BDM research team formed a new company in the course of the program, BDM awarded a lower-tier subcontract to MATSYS to complete BDM's work.
- **Centorr/Vacuum Industries, Inc. (CVI)**, a furnace equipment company, and Wittmer Consultants, Inc., CVI's lower-tier subcontractor, were responsible for continuous sintering development.
- **Deco-Grand, Inc.**, an OEM, was responsible for final production grinding of the valve components.
- **Norton Company, Higgins Grinding Technology Center** (HGTC, formerly World Grinding Technology Center, WGTC), a wheel manufacturer and grinding operation development lab, was responsible for developing valve grinding process/products and technology transfer to Deco-Grand.
- **Chand Kare Technical Ceramics**, a ceramic machining shop, was later added to the team to support ceramic production grinding.
- **IBIS Associates, Inc.**, a materials manufacturing consulting organization, was responsible for ceramic valve manufacturing cost models.

The program was divided into four major tasks.

- **Task 1, Component Design and Specification**
  Task 1a, Preliminary Design
  Task 1b, Final Design
- **Task 2, Component Manufacturing Technology Development**
  Task 2a, Process Cost Modeling
  Task 2b, Environmental Safety and Health Assessment
  Task 2c, Process Control (Systematically develop advanced manufacturing techniques for all the major unit operations: raw material selection, milling, and spray drying, continuous sintering, machining, and inspection.)
  Task 2d, Intelligent Processing (In parallel with the Task 2c, Process Control, develop innovative, intelligent, ceramic processing methodologies for selected unit operations, namely for powder comminution, spray drying, and dry-bag isopressing of valve blanks.)
- **Task 3, Inspection and Testing**
- **Task 4, Process Demonstration**
  Task 4a, Pre-Production (Defining the baseline process at the start of program.)
  Task 4b, Production Demonstration (Scheduled for the end of the program following completion of Task 2, Process Development.)

The engine builder (DDC) and ceramic manufacturer (NAC) worked cooperatively on the design phase of this program (Task 1). A high-power diesel engine valve for the DDC Series 149 engine was selected as the demonstration part for this program. The use of ceramic valves in internal combustion engines offers several advantages. Diesel engines, with their ever-increasing combustion pressures and resultant high thermal loading, are prime candidates for this application. This part was selected for several important reasons: (a) the component would improve engine performance while solving reliability and longevity problems; (b) engine companies were committed to ceramic valve commercialization provided that the related performance, reliability, and cost issues could be resolved; (c) the component size and geometry were representative of a broad class of future ceramic engine components; and (d) the anticipated near-term production volume (28,000 parts) was within the capability of installed capacity and, therefore, cost-reduction efforts could be demonstrated using existing facilities.

Ceramics provide high thermal strength and improved thermal insulation compared to metal components. In the case of engine valves, these characteristics translate into higher peak-firing pressure thresholds, as well as reduced heat rejection to the coolant system, which, in turn, enable an overall increase in engine thermal efficiency. Low density is also a key feature of ceramic valves. In the case of the DDC Series 149 engine, the valve mass was reduced by nearly 60%. Reducing the overall inertia of the engine valve train increased the overspeed capability by 300 rpm (15% of the engine rated speed). In addition, the lighter weight ceramic valves significantly reduced the rocker arm loads.

The critical valve design features were defined based on finite element analysis and actual component testing. Two valve seat angles (30 and 45 degrees) were studied and tested. Four different keeper groove geometries were proposed and investigated. Two valve keeper materials of different hardnesses were considered.

The pre-production valves were manufactured using the SiAlON (NT451) composition to initiate the valve design task and to establish the baseline cost data. The baseline material utilized a relatively high-cost raw material and a complex powder processing methodology. Consequently, it was replaced, later in the program, by an alternate silicon nitride composition (NT551) which utilized a lower-cost raw material and a simplified powder-processing approach. Powder milling utilized the Closed Loop (aqueous) Processing (CLP) methodology developed in a previous DOE program, which assured maximal elimination of intrinsic flaws, and thus enhanced reproducibility.

The material specification was defined based on DDC's expertise with silicon nitride valves. Minimum requirements for material hardness, density, fracture toughness, MOR, Weibull modulus, porosity, and microstructure were specified, along with corresponding measurement standards. Component screening through fixture testing at Norton was also included in the specifications. The valves received at DDC showed good agreement with DDC specifications. No premature failure was observed during proof testing, indicating effective component screening.

Dynamic analysis of the valve-train system was conducted. Model refinements throughout the program enabled excellent agreement between predicted and measured valve-train characteristics. The model was used to assess the overspeed capability gain.

The Task 2 component manufacturing development was performed by all the program team members. In order to reduce the manufacturing cost of the silicon nitride valve, each unit operation of the valve manufacturing process, i.e., powder and slurry preparation, milling, spray drying, valve forming by dry bag isopressing, continuous sintering, machining, and inspection, was critically examined to improve reliability and to reduce overall cost. Cost-effective manufacturing of ceramic valves requires that each sequential process step must be repeatable and controllable. The success of each step has a significant impact on the ease, cost, and yield of each subsequent step.

Using the Technical Cost Model (TCM) developed by IBIS, various alternative approaches were analyzed for their impact on cost. The TCM is a dynamic economic simulation of the manufacturing process and, as such, is capable of exploring the cost impact of changes in production parameters or in the process design. Specifically, the model was applied to examine alternative sintering options, different grinding scenarios, and the impacts of learning improvements and production scale-up effects. With regard to the overall cost, it was no surprise that materials cost, grinding, and sintering were found to be the highest cost drivers.

The cost model developed for this program was successfully applied to examine the relative economics of alternative design and manufacturing scenarios. The model will continue to function as a repository for process information and as a dynamic tool that will allow on-going analysis as input assumptions are updated and modified.

The goal of the spray drying operation is to produce a powder that is both flowable and pressable. Flowability is required for the powder to fill the mold quickly, uniformly, and completely during automated, dry-bag isopressing of valve blanks. A relatively high, uniform, and repeatable powder pressability is required to produce near-net-shape valve blanks that consistently sinter to full density. The development of an Intelligent Control System (ICS) was undertaken to ensure that the properties of the spray-dried powder were uniform, consistent, and repeatable despite inevitable variations in slurry properties and ambient conditions.

Together with NAC researchers at NRDC, BDM/MATSYS successfully developed and demonstrated an ICS for spray drying of silicon nitride powder. Its implementation included: a) hardware upgrades to improve process repeatability and uniformity; and b) the development of a PC-based controller capable of operating the major components of the spray dryer; monitoring, displaying, and recording process data; and actively controlling the residual moisture content of the spray-dried powder. Control of the residual moisture ensures that the powder will have a uniform and consistent pressability. The ICS uses a non-contact infrared moisture sensor to measure the moisture content of the powder on-line, in real-time. A fuzzy logic controller, running on the PC, is used to determine the appropriate control action required to achieve or maintain the desired moisture content.

The integrated Intelligent Control System for the spray-drying operation was demonstrated at NRDC on the prototype spray dryer, was subsequently transferred to the larger production spray dryer at the NAC manufacturing plant, and was successfully brought on-line under this program.

Valve isopressing simulations resulted in a new dry-bag geometry designed to eliminate narrowing of the stem near the initiation of the valve-head radius, to minimize the occurrence of chipping around the valve head, and to enable the production of a pressed blank significantly closer to the net shape of a green machined valve. These objectives were achieved through the design of a bag with a 44% smaller fill volume, which reduced density and stress gradients within the pressed blank. The successful new design was demonstrated at NAC.

Batch-sintered NT551 valves exhibited superior dimensional control as compared to the pre-production NT451 (SiAlON) valves. NT551 valves showed a factor of 3 reduction in valve bending (TIR, or total indicated runout), which directly reduces machining time. Centorr/Vacuum Industries and Wittmer Consultants were responsible for supporting NAC/NRDC in continuous sintering development in the densification process step. Continuous sintering was demonstrated as a viable process to reduce manufacturing cost. The continuous sintered properties of NT451 and NT551 were equal to or better than those measured for the same material formulations sintered in a batch furnace. During the program, significant improvements in valve dimensional control were achieved by optimizing various continuous sintering parameters for both valve materials. The TIR was reduced by over 50%; however, the on average, the TIR was still approximately 2 times greater than for conventional batch sintering. While it is anticipated that further improvements in TIR could be realized by vertical orientation during sintering, due to time and resource constraints, the batch sintering approach was selected for the valve production trials. The IBIS cost model predicted that continuous sintering followed by HIPing offers the most favorable combination of cost and performance. The initial continuous sintering work showed great potential and further development is recommended.

During the ACMT program, four production grinding techniques were considered:

(a) Centerless Plunge Grinding (HGTC and Deco-Grand),
(b) CNC Profile Grinding Using a Studer Grinder (HGTC),
(c) Peel Grinding (Junker Machine), and
(d) Compound Center Grinding (Chand).

NAC and the Norton Company's Higgins Grinding Technology Center (HGTC) initially investigated two different technologies for cost-effectively grinding advanced ceramic valves: (a) plunge centerless grinding for mass (large lot) production, and (b) CNC profile grinding for batch (small lot) production.

(a) To avoid a costly, full-scale production process, the HGTC successfully simulated large production, through-feed centerless plunge grinding of ceramics on a small scale and transferred the technology to Deco-Grand. Various grit and bond combinations were evaluated by HGTC in order to optimize the centerless grinding wheel for material removal rate.

Cost analysis by IBIS showed the centerless plunge technique to be the lowest-cost option at high-production volumes. A limited number of valves were profile ground by Deco-Grand using these wheels. However, dimensional control was found to be less than desirable. Further improvement was expected with better machine tools. Due to time limitations, this approach was abandoned.

(b) Employing a systems approach, HGTC developed a cost-effective CNC Profile Grinding technique capable of machining advanced ceramic valves. HGTC selected appropriate grinding wheel specifications, work piece configuration, CNC machine tool (Studer) and fixturing, plus grinding conditions for both the roughing and finishing operations. In combination, these factors resulted in a total machining time reduction of greater than an order of magnitude. A significant reduction in the rough machining time was accomplished using a high-speed MSL (metal single layered) wheel. A satisfactory reduction in the finishing time was also realized by using a high-bond-strength, vitrified-bonded wheel. The stem diameter of the valves was within ±0.0004 in. (0.01 mm) tolerance, and the surface finish (Ra) was less than 8 μin. (0.2 μm); both met DDC's requirements. The technology was employed to finish more than 30 NT551 valves to qualify the CNC Profile Grinding technique. Subsequently, HGTC ground an additional 150 valves to further validate the CNC grinding approach.

One point highlighted by the IBIS cost model was that the cost and productive lives of grinding wheels have an enormous impact on the grinding cost and total cost of the valves. Therefore, these grinding wheel issues must be targeted and better understood in order to assess current costs more accurately and to reduce costs in the future. A parallel effort by Norton Company under the DOE/ORNL CTP developed an innovative grinding wheel for cylindrical grinding of ceramics. Under this program, the new wheel product was evaluated in the stem grinding of Series 149 engine valves. Incorporation of the new wheel product should further contribute to the reduction of grinding costs.

(c) NAC evaluated the Junker Peel Grinding technique, initially on 10 NT451 valves and, subsequently, on 30 NT551 valves. This grinding approach is somewhat similar to HGTC's CNC profile grinding technique, and is somewhat comparable in cost. NAC observed valve tolerance problems in the 30-valve trial and, consequently, the Peel Grinding technique was not pursued further under the ACMT program.

Based upon the IBIS cost model, the cost projections for the first three grinding approaches are as follows. The plunge centerless grinding process appeared to be the low-cost approach for annual production volumes above 4,000 valves per year. As noted above, use of this technique was discontinued, but further work is recommended. For volumes between 1,000 and 4,000 per year, the Studer CNC profile grinding approach had the lowest cost; below 1,000 per year, Junker had a slight advantage.

(d) A fourth grinding approach was added later in the program. Chand Kare's Compound Center Grinding was somewhat similar to the Deco-Grand Plunge Grinding approach and showed similar cost advantages. However, in the Chand process, grinding marks on the valve head radius were parallel to the stem axis. These marks were predicted to be more benign from a grinding damage perspective.

Both the Chand approach and the HGTC CNC Profile Grinding approach were used in the final valve production demonstration.

In Task 3, testing at DDC consisted of preliminary/screening, overhead fixture, and durability testing. The valves generally showed high capability indices, similar to production part requirements. The screening at DDC included visual inspection of the valves and, when applicable, process capability evaluations were conducted. Preliminary and screening testing were conducted using a valve face pressure fixture (2,500 psi) as well as a valve sealing test fixture (vacuum test). Overhead fixture testing proved the overspeed capability of the valve train system equipped with ceramic valves. Finally, engine durability testing was conducted on a V-8 Series 149 engine using a Mine Haul Cycle.

DDC successfully demonstrated over 1000 hours in the Series 149 diesel engine durability test using both the baseline NT451 SiAlON valves and the later, improved-process NT551 silicon nitride valves. However, there were some NT551 valve failures. The failed valves were ground with some of the new, improved-process, cost-effective machining techniques. Most primary failures of the final design valves were in the fillet radius area. This is the most highly stressed area of the valve, according to finite element modeling results. It was speculated, but not conclusively determined, that machining marks on this surface may have reduced the high temperature fatigue strength of the valve, leading to premature failures. The cause of these failures may also have been due to the rig test design. Further work is needed to confirm and correct the cause, whether it be machining damage, material fatigue, engine design, or a combination thereof.

The IBIS cost model concluded that the highest cost drivers are materials cost, grinding, and sintering. This conclusion was based on projections of a high-volume production scenario that has not yet been implemented. The systematic development of improvements in each of the valve manufacturing process unit operations was validated through the production of 320 fully finished, engine-ready valves. These valves met the dimensional requirements and provided the data to establish a process capability index. By incorporating targeted process improvements (substantially achieved) and the learning curve model (scale-up), the program goal of an order of magnitude reduction in manufacturing cost was attained at a production volume of slightly more than 2,000 valves per year (Figure 1). A factor of 25 cost reduction was established for the modest production volume of 40,000 valves per year. As shown below, without the process improvements, the projected cost reduction is only a factor of 5 for volume increase alone (without ACMT).

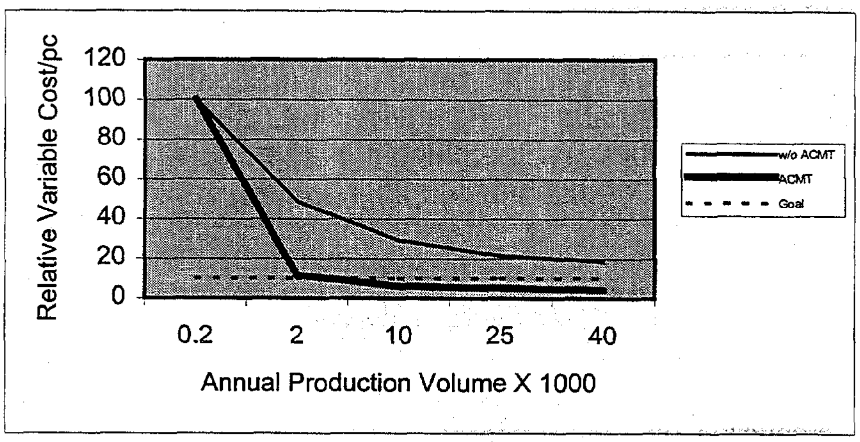

Figure 1. Projected Relative Variable Cost vs Annual Production Volume
Figure 1 shows volume-only cost reduction estimates, without ACMT process improvements; with ACMT process improvements; and the order of magnitude cost reduction program goal.

2. LIST OF TABLES

3. LIST OF FIGURES

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4. ABSTRACT

Advanced structural ceramics are enabling materials for new transportation engine systems that have the potential for significantly reducing energy consumption and pollution in automobiles and heavy vehicles. Ceramic component reliability and performance have been demonstrated in previous U.S. DOE initiatives, but high manufacturing cost was recognized as a major barrier to commercialization. Norton Advanced Ceramics (NAC), a division of Saint-Gobain Industrial Ceramics, Inc. (SGIC), was selected to perform a major Advanced Ceramics Manufacturing Technology (ACMT) Program. The overall objectives of NAC's program were to design, develop, and demonstrate advanced manufacturing technology for the production of ceramic exhaust valves for diesel engines. The specific objectives were (1) to reduce the manufacturing cost by an order of magnitude, (2) to develop and demonstrate process capability and reproducibility, and (3) to validate ceramic valve performance, durability, and reliability.

In order to achieve these objectives, NAC, a leading U.S. advanced ceramics component manufacturer, assembled a multidisciplinary, vertically integrated team. This team included: a major diesel engine builder, Detroit Diesel Corporation (DDC); a corporate ceramics research division, SGIC's Northboro R&D Center; intelligent processing system developers, BDM Federal/MATSYS; a furnace equipment company, Centorr/Vacuum Industries; a sintering expert, Wittmer Consultants; a production OEM, Deco-Grand; a wheel manufacturer and grinding operation developer, Norton Company's Higgins Grinding Technology Center (HGTC); a ceramic machine shop, Chand Kare Technical Ceramics; and a manufacturing cost consultant, IBIS Associates.

The program was divided into four major tasks: Component Design and Specification, Component Manufacturing Technology Development, Inspection and Testing, and Process Demonstration. A high-power diesel engine valve for the DDC

Series 149 engine was chosen as the demonstration part for this program. This was determined to be an ideal component type to demonstrate cost-effective process enhancements, the beneficial impact of advanced ceramics on transportation systems, and near-term commercialization potential. The baseline valve material was NAC's NT451 SiAlON. It was replaced, later in the program, by an alternate silicon nitride composition (NT551), which utilized a lower cost raw material and a simplified powder-processing approach. The material specifications were defined based on DDC's engine requirements, and the initial and final component design tasks were completed.

Component manufacturing development was performed by all program team members. In order to reduce the manufacturing cost of the silicon nitride valve, each unit operation of the valve manufacturing process, i.e., powder and slurry preparation, milling, spray drying, valve forming by dry bag isopressing, continuous sintering, machining, and inspection, was critically examined to improve reliability and to reduce overall cost. Various alternative approaches were analyzed for their impact on cost, using the Technical Cost Model (TCM) developed by IBIS. BDM/MATSYS and NAC researchers at NRDC successfully developed and demonstrated an Intelligent Control System for the spray drying of silicon nitride powder. The ICS for the spray drying operation was demonstrated on a prototype unit and was subsequently made operational at the NAC manufacturing plant. Significant design improvements were made to the dry bag isopressing operation. Continuous sintering was demonstrated and significant improvements in valve dimensional control were achieved. Four production grinding techniques were considered and evaluated. However, only two, CNC Profile and Compound Center Grinding, were used in the process demonstration trials due to component quality requirements.

DDC successfully demonstrated over 1,000 hours in the Series 149 diesel engine durability test using both the baseline NT451 SiAlON valves and the improved-process NT551 silicon nitride valves. Ceramic components provided several important advantages to the Series 149 engine performance. One advantage, 60% reduced weight, reduced the overall inertia of the engine valve train and increased the overspeed capability by 300 rpm. However, NT551 valve failures were experienced in some of the engine tests, the cause of which was not conclusively determined. Further work is needed to confirm and correct the cause, whether it be machining damage, material fatigue, engine design, or a combination thereof.

The systematic development of improvements in each unit operation of the valve manufacturing process was validated by the production of 320 fully finished, engine-ready valves. Incorporating targeted process improvements and the learning curve model (scale-up) achieved the program goal of an order of magnitude reduction in manufacturing cost at a production volume of only slightly more than 2,000 valves per year. A factor of 25 cost reduction was predicted for the modest production volume of 40,000 valves per year utilizing process improvements developed under the ACMT program.

5. INTRODUCTION

Advanced structural ceramics possess useful material properties including high temperature capability, good thermal-shock resistance, low density, high hardness, good corrosion resistance, and high specific modulus. These characteristics make advanced ceramic engine components, manufactured from such materials as silicon nitride, potentially important for reducing energy consumption and pollution in new transportation systems.

5.1 CERAMIC HEAT ENGINE COMPONENT ACTIVITY AT NORTON ADVANCED CERAMICS

In the 1980's several U.S. companies accelerated activity in the development of advanced ceramics for heat engines and other applications. Norton Company's Advanced Ceramics Division continued the development of silicon nitride, silicon carbide, and advanced oxides for wear and corrosion resistant applications. In 1985, the Norton/TRW Ceramics (NTC) Joint Venture was established specifically for developing and commercializing advanced ceramics for heat engine applications. Saint-Gobain Corporation acquired Norton Company in 1990 and the Norton advanced materials businesses became part of Saint-Gobain Industrial Ceramics, Inc. (SGIC), a U.S. subsidiary of Norton Company. In January 1993, SGIC acquired TRW's 50% share of NTC, the former joint venture. This operation in East Granby, CT, became part of the SGIC Norton Advanced Ceramics (NAC) Division, which also produces CERBEC® ceramic bearing components and other nitride, carbide, and oxide advanced ceramics (Figure 2).

Figure 2. NAC Facility in East Granby, CT

NAC was the lead organization on this Advanced Ceramic Manufacturing Technology (ACMT) Program. The SGIC Northboro R&D Center (NRDC) has R&D groups aligned with several SGIC businesses. NRDC has technical services groups that provide support to the business R&D groups, which include mechanical and chemical characterization, NDE, powder processing, forming, furnacing, and machining development. The NAC R&D group at NRDC was a subcontractor to NAC on the ACMT program.

5.2 DOE/INDUSTRY PROGRAMS TO OVERCOME BARRIERS TO COMMERCIALIZATION

It has long been recognized by industry and government that the major barriers to commercialization of advanced ceramics are performance, reliability, and manufacturing cost. The DOE Office of Transportation Technologies (OTT) initiated the Ceramic Technology Project (CTP) in 1983 at Oak Ridge National Laboratory [1]. The overall objectives of CTP were to develop highly reliable, advanced structural ceramics for advanced heat engines, including automotive gas turbine and heavy duty diesel engines. Approaches to achieving reliability were: to develop tougher ceramics, to develop a processing technology that reduces flaws, to perfect mechanical testing and time-dependent property characterization, and to develop a life-prediction methodology. DOE OTT sponsored several cost-shared programs with industry, universities, and national labs. A major Advanced Processing Program [2] was led by Norton Company's NRDC, now Saint-Gobain Industrial Ceramics, Inc. (SGIC), with the objective of demonstrating ceramic reliability. This program developed process methodologies to reduce flaws in high-temperature silicon nitride buttonhead tensile specimens. The program approach was to implement in-process inspection, nondestructive evaluation, statistical process control, mechanical characterization, and proof testing into both the injection molding and pressure slip casting processes. The Advanced Processing Program, utilizing a new closed-loop aqueous process, exceeded program objectives for both tensile strength and the demonstration of reliability.

In a parallel effort to the CTP, the DOE Advanced Turbine Technology Applications Program (ATTAP) continued the development of automotive gas turbine systems [3,4]. Several ceramic components were incorporated into these advanced turbine engines as enabling materials. The two ATTAP prime contractors were AlliedSignal Aerospace and Allison Engine Company. Norton/TRW Ceramics was a major ceramic component supplier to both contractors. The ATTAP Program led to further advancements in advanced ceramic processing technology and demonstrated ceramic engine component performance advantages.

CTP included the development of ceramic materials for both automotive gas turbine systems and diesel engines. Later in the CTP, DOE Propulsion Materials efforts were divided between the Office of Heavy Vehicle Technologies (OHVT) and the Office of Advanced Automotive Technologies (OAAT). The recent CTP initiatives, such as Cost-Effective Ceramics (described in Section 5.3) and Ceramic Machining, are now under Heavy Vehicle Propulsion Materials (HVPM) of OHVT.

HVPM supports the materials needs of OHVT to reduce fuel consumption and pollution emission in Class 1-8 trucks.

Diesel engine materials also are becoming more important in the OAAT. Toward the end of ATTAP, there was a greater emphasis put on improved diesel engine materials because of inherent diesel engine efficiency advantages and the potential for meaningful energy savings in heavy vehicle systems. Also, both gas turbine and diesel systems were being developed in the new automotive hybrid electric vehicle (HEV) programs. Subsequently, the gas turbine activity was dropped by the DOE OTT in HEV systems.

5.3 DOE/ORNL COST EFFECTIVE CERAMICS INITIATIVE

Technological developments in both materials and processing have enabled ceramic components to be fabricated and evaluated in a wide variety of rig tests or in actual engines. Results show that ceramic hardware has performance advantages and the necessary reliability for operating engines. It appears, therefore, that technical barriers to commercialization will be overcome. However, from a business perspective, cost remains a significant impediment. Ceramic components range from one to several-hundred times the cost of their metal counterparts. Engine builders indicate willingness to commercialize this material pending achievement of acceptable costs.

With advanced ceramic component reliability demonstrated, DOE and industry attempted to address the cost barrier to ceramic utilization. Realizing that the successful commercialization of advanced ceramics depended on a significant reduction in manufacturing costs without compromising reliability, the Cost Effective Ceramics (CEC) effort was initiated under the CTP in 1993. The CEC effort is part of the Heavy Vehicle Propulsion Materials Program of OHVT. An early study program that analyzed the major cost factors in ceramic engine component manufacturing unit operations was conducted by NTC as part of the CTP [5]. NTC, other ceramic suppliers, and DOE identified the major cost drivers in ceramic manufacturing. These include machining, inspection, raw materials, forming, and densification.

The CTP selected three major Advanced Ceramic Manufacturing Technology (ACMT) Program Teams that became the backbone of the Cost-Effective Ceramics Initiative [6]. All three programs involved selected ceramic component manufacturing demonstrations and addressed the major elements of cost modeling, densification, ceramic machining, powder processing, in-process controls, intelligent processing, testing, and performance acceptance.

- The SGIC, **Norton Advanced Ceramics (NAC) Team** included Detroit Diesel Corporation (DDC), SGIC Northboro R&D Center (NRDC), Norton Company's Higgins Grinding Technology Center (HGTC, formerly World Grinding Technology Center), Deco-Grand, Inc. BDM Federal, Inc.,/MATSYS, Inc., Centorr/Vacuum Industries (CVI), Wittmer Consultants, and IBIS Associates, Inc. The principal component was a silicon nitride valve for the DDC Series 149 diesel engine.

- The **Kyocera Industrial Ceramics Corporation Team** included Caterpillar Inc., and Schwitzer U.S., Inc. The principal component was a silicon nitride diesel turborotor.
- The **Golden Technologies Company Team** included Eaton Corporation, Cummins Engine Company, and DDC. The principal components selected were a transformation-toughened zirconia fuel injection timing plunger and a DDC Si3N4 clevis pin.

The NAC program was the only ACMT program brought to a conclusion. Kyocera withdrew from the ACMT program after the initial design milestone. Golden Technologies withdrew from the program soon after award, following a restructuring of their business. However, the efforts of the Golden Technologies ACMT team led to the commercialization of an advanced ceramics engine component. To date, greater than one million zirconia fuel injector plungers have been manufactured.

Cost-Effective Ceramic Machining (CECM) was a subset of the Cost-Effective Ceramics effort. ORNL and industry recognized the importance of ceramic machining as a major cost driver [7,8]. Several programs were implemented to address machining methodologies, the development of innovative grinding wheels, and machinability testing. One new program, led by Norton Company Superabrasives Division, had the objective of developing an innovative grinding wheel for cost-effective cylindrical grinding of advanced ceramics. Demonstrating synergy among the ORNL programs, NAC and Norton's HGTC participated in Phase II of the Innovative Grinding Wheel Program by evaluating the new experimental wheel in valve stem grinding of NAC silicon nitride valves from the ACMT Program [9].

5.4 NAC ACMT TEAM PROGRAM PLAN

5.4.1 ACMT Program Objectives

The NAC ACMT program plan was to develop a cost-effective manufacturing process for high-power diesel engine valves for Detroit Diesel Corporation's Series 149 engine. This part was selected for the following important reasons.

- Ceramic valves would improve engine performance while solving reliability and longevity problems.
- The engine companies and their OEM suppliers were committed to ceramic valve commercialization provided that the related performance, reliability, and cost issues could be resolved.
- The size and geometry of the part were representative of a broad class of future ceramic engine components.
- The anticipated near-term production volume (28,000 parts) was within the capability of installed capacity. Therefore, cost-reduction efforts could be demonstrated using existing facilities.

NAC's ultimate objective in participating in this program was the commercial introduction of ceramic components, which would help to achieve DOE OTT energy conservation and pollution control objectives for heavy vehicle engines. NAC's commercialization objective was to be achieved, in part, by accomplishing the following ACMT program goals:

- Demonstration of at least an order of magnitude reduction in manufacturing cost for each component.
- Demonstration of process capability values (Cpk, or 6 times the standard deviation divided by the tolerance) of 0.7 or less for all critical component attributes.
- Validation of the component performance, durability, and reliability through rig and engine testing.

5.4.2 Material Selection

NAC's NT451 SiAlON was the valve component ceramic material used to initiate the design task and to establish the baseline cost data. Originally developed as part of the Norton/TRW Ceramics joint venture, the processing and component fabrication of this material were performed in NAC's manufacturing facility in East Granby, Connecticut. Within this facility, NAC had assembled state-of-the-art forming, firing, machining, and inspection equipment. Between 1989 and the inception of the ACMT Program, NAC produced and supplied to most of the world's major engine builders over 10,000 NT451 ceramic parts, gaining significant processing and component manufacturing experience in the process.

The SiAlON baseline material utilized a relatively high cost raw material and involved complex powder-processing methodology. Therefore, it was replaced, later in the program, by an alternate silicon nitride composition (NT551) which utilized a lower cost raw material and a simplified powder-processing approach. Further, powder milling utilized the Closed Loop [aqueous] Processing (CLP) methodology developed in a previous DOE program [2], which assured maximal elimination of intrinsic flaws and thus enhanced reproducibility.

5.4.3 ACMT Team

To achieve the ACMT program goals, NAC assembled a vertically integrated industry team. Collectively, this team included professionals with a broad base of experience in ceramic component development and manufacturing and in engine design and testing.

- Saint-Gobain Industrial Ceramics, Inc., (SGIC) Norton Advanced Ceramics (NAC) Division — A leading advanced ceramic manufacturer. Responsible for ceramic process development, manufacturing, and program management. East Granby, CT, would be the principal component manufacturing location.
- Detroit Diesel Corporation (DDC) — Major heavy-duty diesel engine manufacturer. Responsible for component design, inspection, and testing.

• Saint-Gobain Industrial Ceramics, Inc., (SGIC) Northboro R&D Center	Ceramic research center, includes NAC R&D group and technical support. Responsible for developing ceramic processes utilizing process control and intelligent processing methodologies.
• BDM Federal, Inc. • MATSYS, Inc.	A leader in advanced manufacturing systems and technologies. Responsible for developing and demonstrating intelligent processing procedures. When the BDM research team formed a new company in the course of the program, BDM awarded a lower-tier subcontract to MATSYS to complete BDM's work.
• Centorr/Vacuum Industries, Inc. • Wittmer Consultants, Inc.	A leading industrial furnace manufacturer and their lower-tier subcontractor, Dr. Dale Wittmer, a continuous sintering researcher from Southern University Illinois. Jointly responsible for developing and demonstrating continuous sintering of valves.
• Deco-Grand, Inc.	A high-volume, precision production grinding and machining OEM. Responsible for the final production grinding of valves.
• Norton Company, Higgins Grinding Technology Center (HGTC)	The leading grinding wheel manufacturer and grinding process development lab. Responsible for developing ceramic machining processes/products for the component and technology transfer to Deco.
• Chand Kare Technical Ceramics	A leading ceramic machining shop. Chand was added later in the program to support machining development and production grinding.
• IBIS Associates, Inc.	An advanced materials consulting organization. Responsible for developing the ceramic valve manufacturing cost model.

5.4.4 ACMT Program Approach and Tasks

To meet the objectives, the program was divided into four major tasks.

Task 1, Component Design and Specification

Task 1a, Preliminary Design: NAC and DDC engineers were to work cooperatively on this subtask and submit the preliminary design package to ORNL in fulfillment of the first major milestone. DDC built upon their experience with ORNL under a separate CRADA, using finite element analysis of the valve seat angle and keeper groove geometry to finalize this valve design.

Task 1b, Final Valve Design: The valve design would be finalized after completion of the program manufacturing development and prototype testing tasks.

Task 2, Component Manufacturing Technology Development

Task 2a, Process Cost Modeling: IBIS and NAC's joint activity was to perform a cost sensitivity analysis of all of the unit operations in Task 2.

Task 2b, Environmental Safety and Health: The SGIC Environmental Health and Safety Program Administrator was to conduct a detailed audit specific to the proposed cost effective processes for the selected components to ensure regulatory compliance and employee safety. All areas of ES&H were to be considered including chemical safety, employee training, and requirements for protective clothing and respiratory protection, air monitoring, waste disposal, air quality, and water discharge. NAC's NT451 SiAlON baseline process had been part of an ongoing audit prior to the ACMT Program, and had been determined to be fully compliant with all local, State, and Federal occupational safety and environmental protection regulations. Additionally, the proposed manufacturing process was expected to be similarly benign.

Task 2c, Process Control: The process-control subtask, to be performed by the entire ACMT Team, was to systematically develop advanced manufacturing techniques for all of the major unit operations: raw material selection, milling and spray drying, continuous sintering, machining, and inspection. The NRDC team comprised several researchers who worked on the successful CTP, Improved Processing for Reliability Program [2]. The lessons learned from this program, which resulted in the making and characterizing of highly reliable advanced ceramics using an aqueous system, were applied to ACMT. Figure 3 shows the baseline manufacturing steps for making ceramic valves. From left to right, the figure shows the valve after green forming, after green machining, after densification, and after final machining.

Figure 3. Baseline Process Ceramic Valve Manufacturing Steps

Task 2d, Intelligent Processing: Innovative, intelligent ceramic processing methodologies were to be developed in the unit operations of powder comminution, spray drying, and dry-bag isopressing of valve blanks. These would incorporate mathematical models of the processes to augment the expert rule based systems. Prior to ACMT, a drawback of the process was the limited yield of materials that met specifications. By defining appropriate on-line sensors capable of feedback in real-time, the yields were expected to improve dramatically. Figure 4 depicts the pre-ACMT off-line process optimization and the ACMT plan to develop on-line, intelligent control systems.

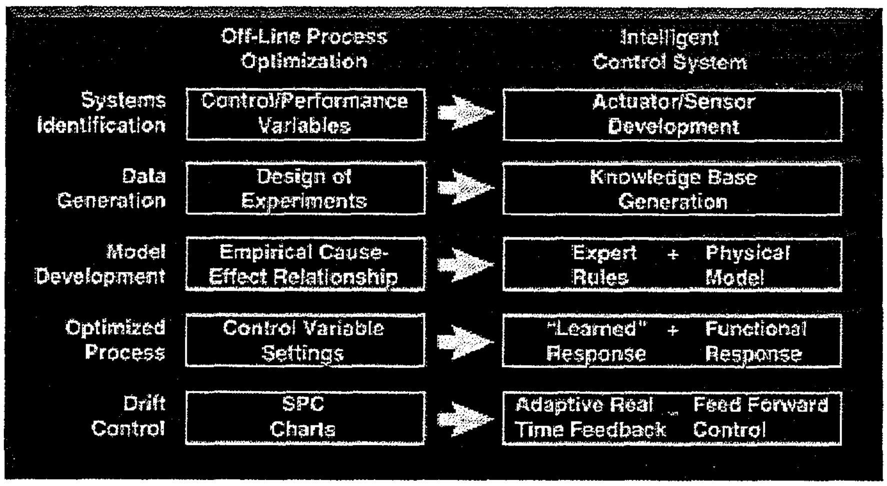


Figure 4. Schematic of the Off-Line Process Optimization and Program Plans to Develop On-Line Intelligent Control Systems

Task 3, Inspection and Testing

The component fabrication was part of Task 4a (Pre-Production). Using the preliminary design from Task 1a, the components would be fabricated by NAC and delivered to DDC. This hardware was to be rig tested by DDC to validate the preliminary valve design.

Task 4, Process Demonstration

Task 4a, Pre-Production: As the first activity of the ACMT Program, two hundred preliminary design valves (from Task 1a) were to be fabricated using the baseline NAC valve prototype manufacturing procedures.

Task 4b, Production Demonstration: This subtask was scheduled for the end of the program after the Task 2 Process Development had been completed. It was anticipated that this subtask would manufacture and deliver a production demonstration set of final design valves to demonstrate achievement of the quality and cost objectives.

6. OBJECTIVE/SCOPE

The objectives of this program were to design, develop, and demonstrate advanced manufacturing technology for the production of ceramic valves. Using the production manufacturing process for a ceramic exhaust valve for DDC's Series 149 diesel engine as a basis, the specific objectives were to:

1) Reduce manufacturing cost by at least an order of magnitude over current levels;
2) Develop and demonstrate process reproducibility by achieving process capability values (C_{pk}) of 0.7 or less for all critical component attributes; and
3) Validate ceramic valve performance, durability, and reliability in rig and engine testing.

7. RESULTS

7.1 COMPONENT DESIGN AND SPECIFICATION - TASK 1

7.1.1 Preliminary Design - Task 1a

Two-dimensional finite element analysis of the valve seat angle and keeper groove geometry was performed by ORNL under a DDC-ORNL CRADA. In addition to modeling a 30° seat angle from the production metal valve, a 45° seat angle was also modeled. Three different keeper geometries were modeled and compared. These three geometries represent groove configurations from: (1) the current production Series 149 valve, (2) the Series 60 exhaust valve, and (3) the ceramic valve tested under the Advanced Diesel Engine Component Development (ADECD) Program.

Each load combination that occurred during the valve cycle was analyzed. When pressure (2,300 psi), spring force (100 lbs), and thermal loading act simultaneously when the valve is closed, the maximum principal stresses on the valve seat were significantly larger than when pressure alone was applied. The stress values for this case are shown in Table 1.

Table 1. Computed Operating Stresses in a Ceramic Valve

	Maximum Principal Stress (Ksi)	
Location	30°	45°
Seat Radius (midway between seat and stem)	29.2	22.6
Seat (in insert contact region)	27.3	25.3

Since the mean strength of NT451 at the temperatures of interest is 113 Ksi, the POS (possibility of survival) calculations gave a value of 1.0 for all cases. Fatigue and other factors may, however, reduce the strength significantly. The 45° seat angle valve has a 23% lower maximum tensile strength in the underhead radius, and a 7% lower stress in the seat. The lower stress in the underhead radius is probably due to the fact the 45°-seat-angle allows the valve to slide more easily on the insert. The lower stress with the 45° seat angle configuration will likely come at the expense of increased wear. In order to determine the trade-off between underhead radius stress and seat-angle wear, DDC and NAC elected to fabricate both 30° and 45° seat-angle prototype valves.

The three keeper-groove options were modeled with 300 lb of closing force. The calculated maximum principal stresses are summarized in Table 2.

Table 2. Calculated Maximum Principal Stresses

Case	Maximum Principal Stress (Ksi)
Standard	15.4
Option 1	15.6
Option 2	15.7

All of these maximum stresses were on the surface of the groove, upward from the groove center line. Based on these results, the standard keeper-groove design was recommended for the preliminary-design ceramic valve.

DDC modified valve drawing DD-125232 to incorporate the lowest stress design. Two ceramic valve part Nos. were created: DD-125232-D for a valve with a 30° seat angle, and DD-125233-ND for a 45° seat-angle option. Based on these modifications, NAC completed all shop drawings and technical specifications comprising the preliminary design package. This preliminary design package was forwarded to ORNL in fulfillment of Milestone No. 1, and final approval was obtained in preparation for valve fabrication.

In support of valve-design optimization, NAC utilized its standard axial-pull proof test apparatus to purposely fail a total of 11 finished NT451 SiAlON Series 149 valves. The purpose of this activity was to determine the actual failure load and compare it with the FEA modeling results. A summary of the valve axial-pull-testing data is provided in Table 3. Over 50% (6 of 11) of these valves broke at the base of the lock at loads ranging from 3,530 lb to 4,275 lb. The nature of the fracture surfaces for these valves indicated failure from a bending load.

Table 3. Axial-Pull Testing to Failure Summary Using Standard Lock Design

Test No.	Part ID	Failure Load (Lb)	Location of Break	Uniform Witness Mark
1	295	4,087	Bottom of Lock	No
2	235	3,618	Stem	No
3	282	4,898	Lock Groove	Yes, Very Distinct, Uneven at Bottom
4	288	3,449	Bottom of Lock	No
5	230	4,275	Bottom of Lock	No - Non-uniform, 2 Places at Gaps in Lock Halves
6	179	4,240	Lock Groove	Yes
7	281	3,898	Bottom of Lock	No - Non-uniform, 2 Places at Gaps in Lock Halves
8	217	4,297	Lock Groove	Yes
9	248	3,710	Bottom of Lock	No - Non-uniform, Mark One Side of Stem Diameter
10	431	3,530	Bottom of Lock	No
11	450	$\geq$ 4,000	Lock Groove	Yes

As correlated by the degree of uniformity of copper witness marks on the ceramic valves, it is believed that the DDC-supplied, two-piece, copper-coated locks did not always load the stems in a uniform manner.

NAC designed and fabricated an alternate lock design in an attempt to eliminate the bending failure mode and to increase the break load. This lock design incorporated more contact area on the stem and tighter dimensional control. Eleven (11) additional finished valves were axial-pull tested to failure. A summary of these results is provided in Table 4. The modified lock design reduced the frequency of breakage at the base of the lock by a factor of two, and increased the average break load from 4,000 ± 424 lb to 5,220 ± 879 lb. This lock design was reviewed by DDC, and implemented for use in the final valve design. A detailed assessment of the benefit of this lock design versus the additional cost will be addressed in Task 2.

Table 4. Axial-Pull Test to Failure Summary Using Alternate Lock Design

Test No.	Part ID	Failure Load (Lb)	Location of Break	Uniform Witness Mark?
1	460	5,730	Lock Groove	Yes
2	417	4,637	Stem	Yes
3	413	6,008	Lock Groove	Yes
4	532	4,785	Stem	Yes
5	471	6,009	Lock Groove	Yes
6	357	5,191	Lock Groove	Yes
7	469	3,013	Bottom of Lock	Yes
8	319	4,930	Bottom of Lock	Yes
9	526	5,494	Bottom of Lock	Yes
10	374	5,521	Stem	Yes
11	486	6,011	Stem	Yes

DDC Material Specification 15T-4/S149, "Engineering Product Approval Requirements for Experimental SiAlON Exhaust Valve," was established. Mechanical properties of the most recent batches of NT451 SiAlON were analyzed and taken into consideration in preparing this document. This material specification was included as part of the preliminary design package. Based on the above design and analysis efforts, valves were fabricated for 500-hour durability testing.

One of the valve proof tests specified in DDC Specification 15T-4/S149 is a valve face pressurization test. DDC designed and fabricated a fixture to conduct this test on the preliminary design valves. The test fixture utilized pressurized nitrogen to apply a 2,500-psi load to the valve face. Four valves were tested at one time, at a rate of 16 valves per hour.

Eighty 30° seat valves received by DDC were visually inspected and tested in the face pressure fixture with no failures. These parts were also vacuum checked per DDC Specification 67T-2, "Intake and Exhaust Valve Sealing Test Procedure," and qualified for overhead fixture testing as described in Task 3.

Dynamic modeling of the Series 149 valve train, using the PC version of ADAMS software, was performed to compare the performance of ceramic valves with that of standard metal valves. The details of this analysis are described in Task 3.

7.1.2 Final Design - Task 1b

The Series 149 engine valve design was finalized at the completion of:

- finite element stress analysis using operating load conditions,
- pull tests,
- the valve train dynamic modeling, and
- the 500-hour engine durability test.

The Series 149 valve-train model was used to predict the dynamic characteristics of ceramic valves. The following improvements were predicted:

- lower seating velocity, which reduces valve-to-seat impact force,
- increased no-follow speed, which allows the valve train to sustain faster engine speeds, and
- reduced loads on the rocker arm, as well as other valve-train components, due to lower valve train inertia.

The 500-hour durability test of the ceramic valve in the 8V-149 engine was completed without any adverse incidents. The valves were analyzed in the material laboratory at DDC, and all were found to be in excellent condition with no significant wear on the seat or in the keeper groove area.

Based upon the above test results, the finalized valve design incorporated a 30° seat angle and a keeper groove with chamfers on the bottom side and a radius on the topside. In addition, DDC's soft keepers were selected over production keepers.

7.2 COMPONENT MANUFACTURING TECHNOLOGY DEVELOPMENT-TASK 2

7.2.1 Process Cost Modeling - Task 2b

IBIS Associates, Inc., was subcontractracted to develop and apply a process cost model for the fabrication and manufacture of silicon nitride valves.

The goal of the cost-modeling effort was to establish the baseline costs of valve manufacturing at the beginning of the program, to understand the resulting cost reduction from specific process improvements, and to aid in making decisions on process design alternatives. By employing this type of economic analysis at an early stage of process development, the chances of commercial success were considerably improved by providing an understanding of the overall manufacturing cost structure, by focusing developmental resources on issues that have the greatest impact on cost, and by establishing specific technical goals required to meet the cost targets of the market.

In the first stage of the cost-modeling program, IBIS developed a baseline model of the valve-manufacturing process utilized by Norton Advanced Ceramics. This model was verified through comparison with actual expenses experienced by the manufacturing operation. In the second stage of the program, the model was applied to project cost under alternative manufacturing scenarios to learn the impact on cost of a number of critical cost drivers through the application of sensitivity analyses. In the third stage of the program, the model was applied to the understanding of several critical process design issues, with particular focus on sintering alternatives, grinding scenarios, and the improvements resulting from learning and economies of scale. The results and findings of these analyses are detailed following.

7.2.1.1 Technical Cost Modeling.

Technical Cost Modeling (TCM) is a computer-based spreadsheet technique used by IBIS Associates, Inc., to simulate manufacturing costs beginning with the flow of operations that make up a process or technology. The technique is an extension of conventional process modeling, with particular emphasis on capturing the cost implications of material and process variables, and changing economic scenarios. This technique enables evaluation of product cost comparisons and the sensitivity of these costs to changes in product and process design.

In TCM, each manufacturing step is broken down into separately calculated individual elements including materials, capital equipment, labor, energy, and other expenses (e.g., maintenance, tooling, building space). Using a set of accounting assumptions, specific step parameters (e.g., cycle time, yield) and manufacturing product information (e.g., annual production volume, capacity, non-dedicated or dedicated equipment) are used to calculate as a function of the product design each individual process element. As a result, critical cost parameters can be identified for each process step through sensitivity analysis.

The Ceramic Valve Manufacturing TCM developed for this program is capable of evaluating the production economics of a number of alternative process paths involving up to 22 individual operations, with the resolution of breaking down cost by element for each individual step.

7.2.1.2 Process Assumptions.

The valve manufacturing process, as modeled, is illustrated by the flow chart in Figure 5. The dotted lines and parallel production paths depict optional production routes or operations that can be examined by the model. For instance, one powder formulation (NT451, SiAlON) required a pre-sintering step while the other (NT551) did not, so this operation could be turned on or off.

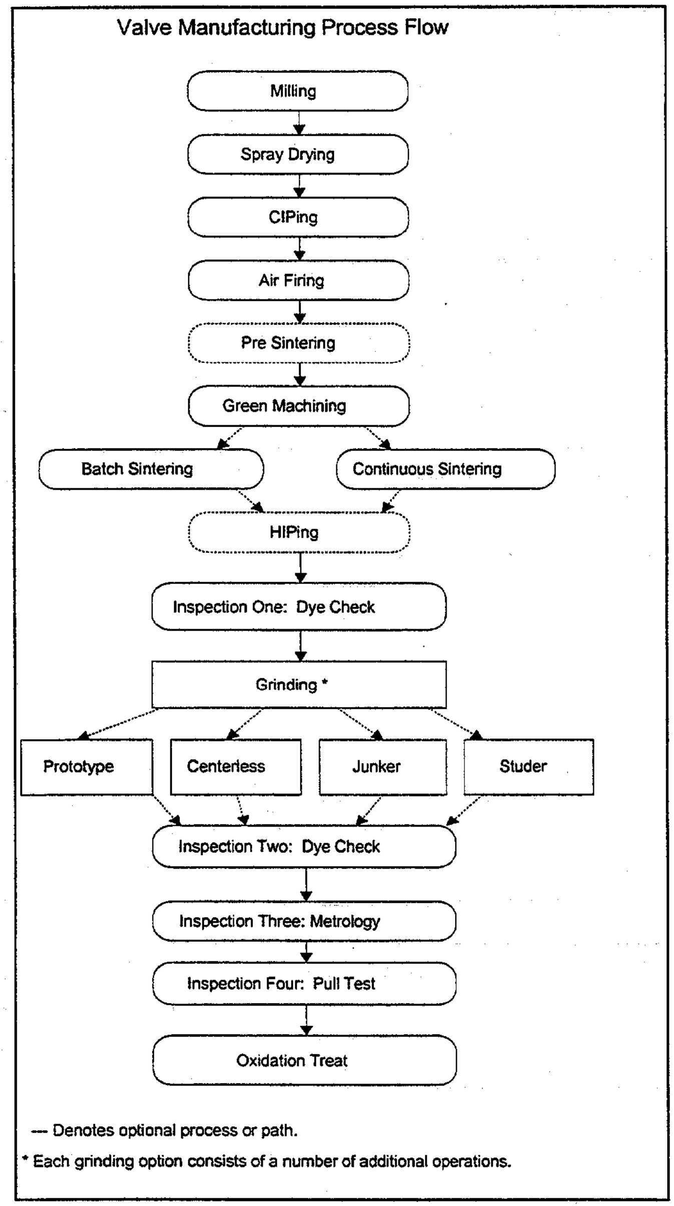


Figure 5. Valve Manufacturing Process Flow

For the analyses described later in this document, the functionality of selecting batch or continuous sintering, the inclusion of HIPing step, or choosing one of three different grinding scenarios was included. It should also be noted that although each of the grinding alternatives is depicted by a single box, in the model they each consist of five to eight separate operations, the details of which are listed in the Grinding Scenarios section.

For the baseline cost results, a high-production-volume scenario was assumed, with volume material prices and higher yields than are currently experienced. This scenario, as described in the learning and volume effects section of this report, is the basis for making long-term decisions in terms of product and process design.

The costs of this baseline scenario are presented by operation in Figure 6. It should be noted that these baseline costs are for a specific production scenario of 40,000 parts per year with high-production-volume material prices and yields as defined in the "1999" scenario in the Learning and Scaling Improvements section. It is seen here that by far, the highest cost factor is the cost of grinding, followed by material cost and the cost of sintering. For these reasons, the grinding and sintering processes have been targeted for further analysis to explore the potential for cost reduction. Figure 7 displays the results of a simple sensitivity analysis of total valve cost to changes in annual production volume. It is shown that the greatest cost reduction occurs up to 20,000 parts per year, above which there is relatively little cost reduction. As will be shown later, this is due to the high cost contribution of grinding wheels, and their relatively short production lives.

7.2.1.3 Grinding Scenarios.

The model was applied to understand the economics of alternative grinding scenarios. The three alternatives analyzed here are the Vendor B centerless grinding process, the similar Vendor A CNC grinding process employing a Studer machine, and the Vendor D peel grinding process. The grinding time and equipment investment assumptions were based on a detailed process audit of each of the three grinding procedures. The variable (labor and energy) and fixed (equipment, tooling, and other miscellaneous) costs were obtained from the actual manufacturing set up in place. The grinding cost breakdown by element for the three grinding procedures is shown in Figure 8, while the sensitivity to production volume for the three grinding techniques is shown in Figure 9. The resulting data show that the Centerless grinding process is the low-cost approach at annual volumes above 4000 valves per year.

Figure 8 and Figure 9 also show that although tooling (grinding wheel) cost is greater, faster throughput and lower equipment investment allow economies of scale at higher volumes. Tooling in this analysis is the cost of grinding wheels, and as mentioned previously, the productive lives and costs of many of the grinding wheels for this analysis have been estimated based upon historical data.

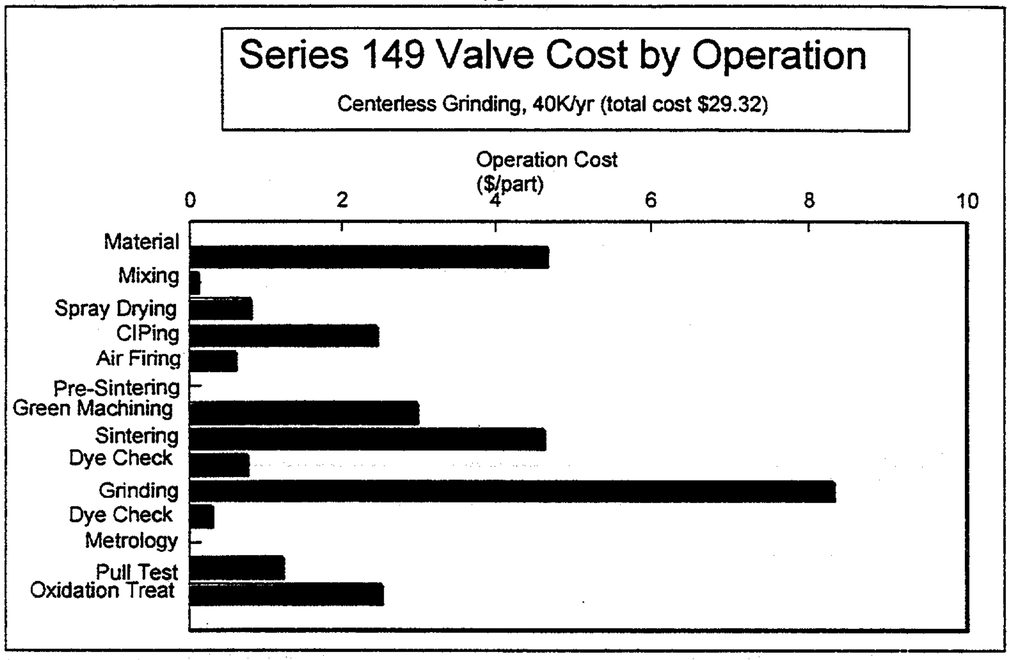


Figure 6. Valve Cost by Operation

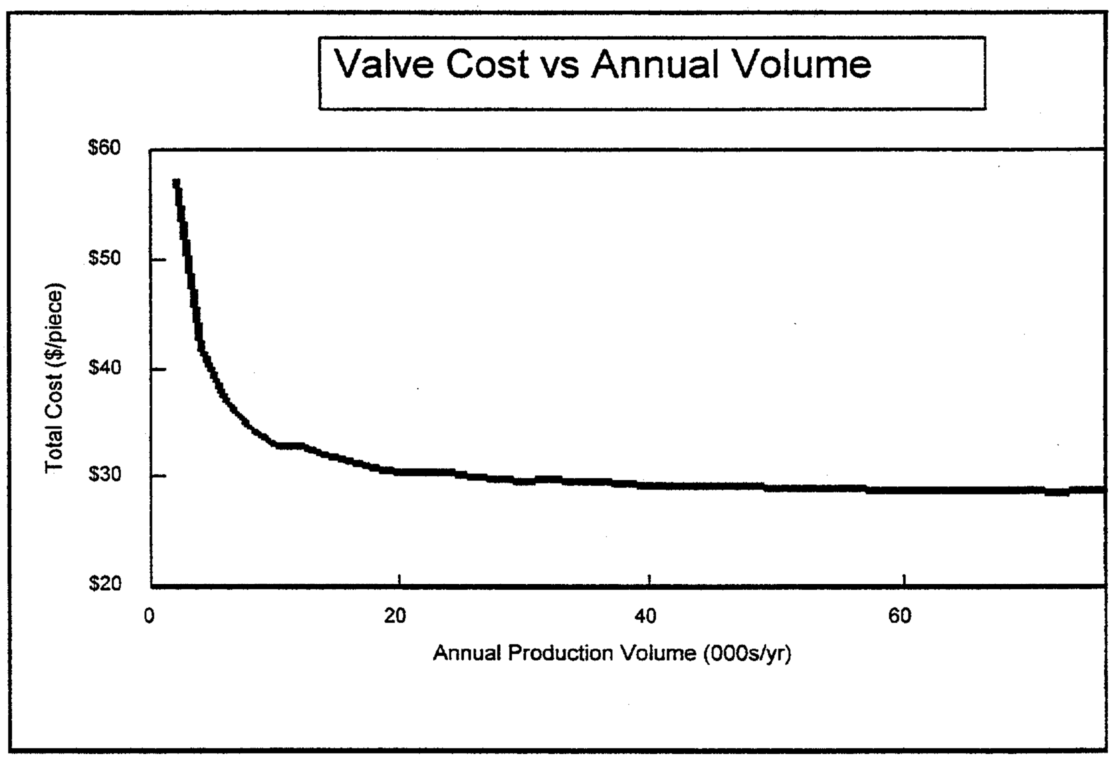


Figure 7. Valve Cost vs Annual Volume

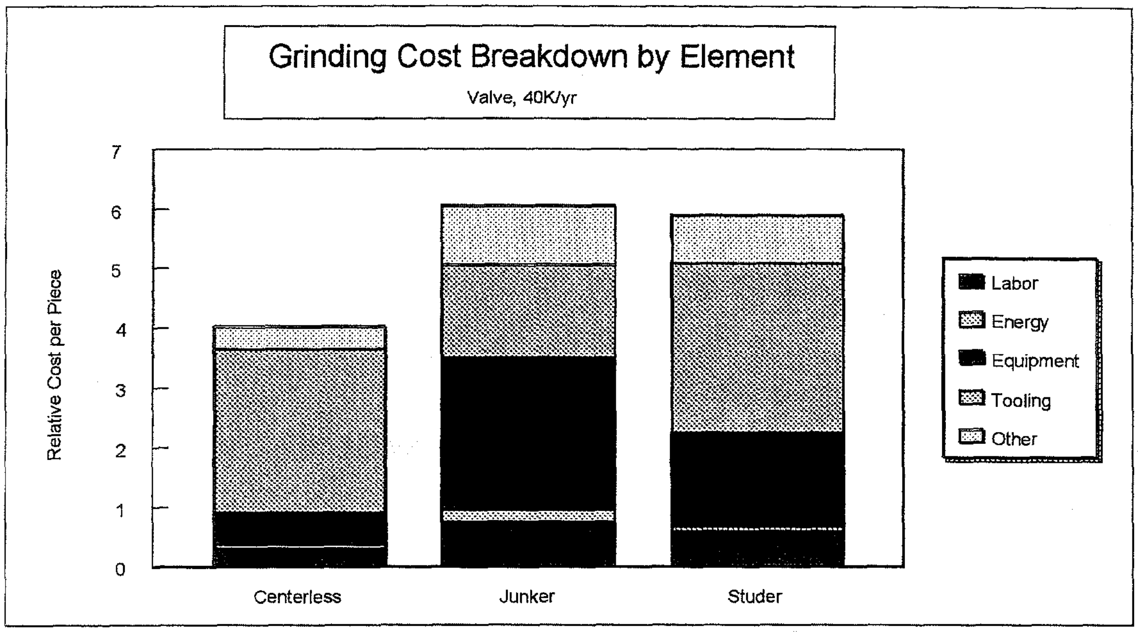


Figure 8. Grinding Cost Breakdown by Element

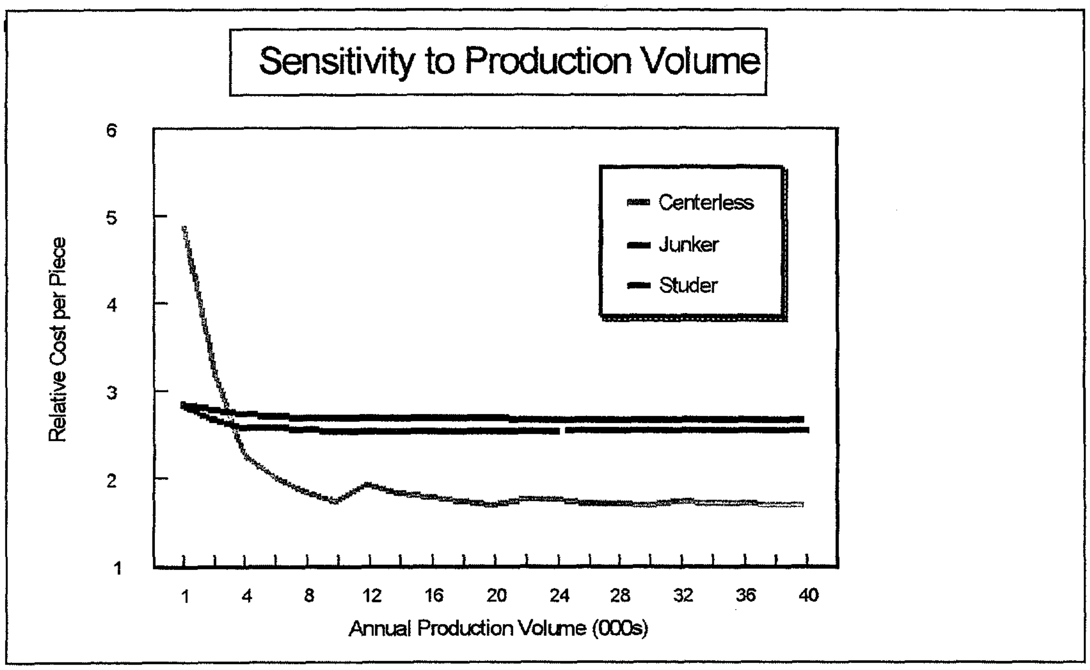


Figure 9. Cost Sensitivity to Production Volume

Later in the program, Vendor C, with a modified centerless grinding approach (Compound Centerless Grinding) was engaged. The cost estimate per valve was computed to be very close to the centerless grinding cost described in Figure 9. This further verifies the promise of the centerless grinding approach.

7.2.1.4 Sintering Analysis.

After the costs of materials and grinding, the most significant cost element has been shown to be that of sintering. Furthermore, alternative sintering procedures have a great effect on finished part performance and reliability. Therefore, five different sintering approaches have been defined and are analyzed here. The five scenarios consist of four different operations as shown in Figure 10. The scenarios are: batch sintering alone (to which the four alternate procedures should be compared), continuous sintering alone, batch sintering followed by HIPing, continuous sintering followed by HIPing, and a one-step, gas-pressure sintering (GPS).

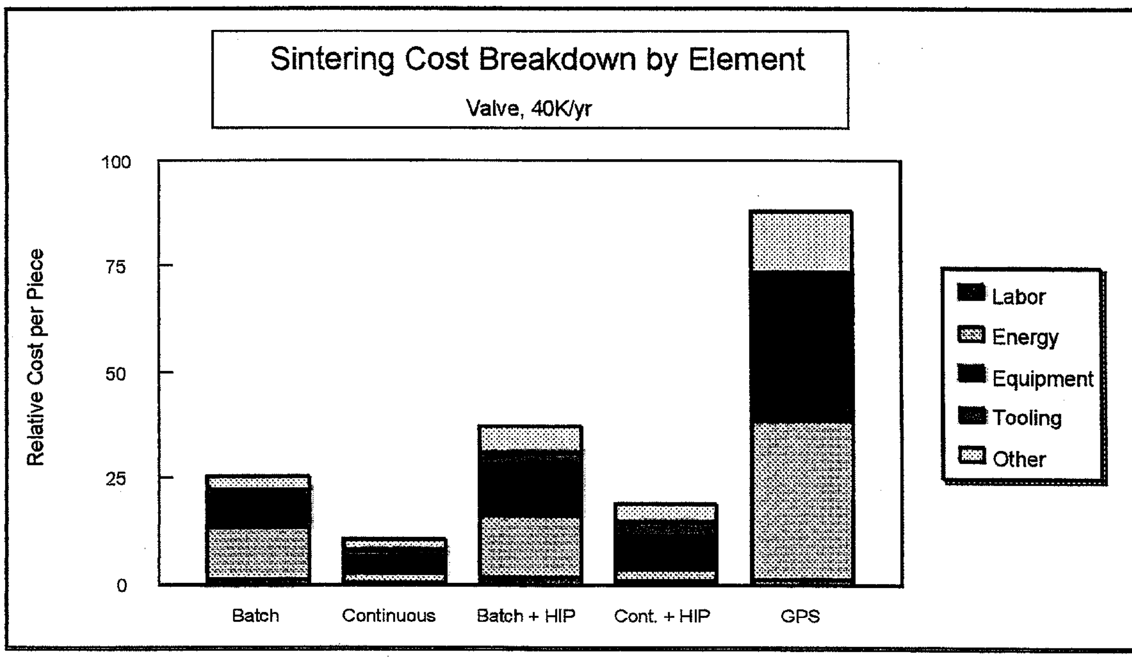


Figure 10. Sintering Cost Breakdown by Element

Batch Sintering. This process consists of loading the parts onto fixtures, loading them into the furnace, running through the firing cycle, and unloading the fixtures and parts. This approach has high equipment and energy costs because of the high residence time in the furnace. Batch sintering alone resulted in only moderately acceptable sintered density of the valves, so an additional batch plus HIPing scenario was examined to achieve more acceptable density.

Continuous Sintering. The continuous-sintering scenario reflects the process design by Wittmer Consultants and Centorr Vacuum Industries. In order for continuous sintering to be economical, throughputs of above six parts per hour must be achieved. The assumption of fifteen valves here requires a wider furnace opening than the original design to accommodate crucibles carrying three valves each. Another assumption for this production scenario is the inclusion of additional air-lock equipment to minimize the loss of nitrogen. Continuous sintering alone did not yield acceptable density of the finished valves, so an additional continuous sintering followed by HIPing was examined.

HIPing. Hot Isostatic Pressing involves the application of very high pressure for an extended length of time to fully densify ceramic or metal powders. In order to be HIPed, parts must have an impermeable surface after sintering. Because of the extended time in a high pressure vessel, this operation incurs high energy and equipment costs.

GPS. The gas-pressure-sintering process is a combination of batch sintering and HIPing (at lower pressure) in one step. An expensive high pressure furnace sinters the valve at high temperature. The high cost of equipment and the relatively small batch size result in very high energy and equipment costs.

A cost comparison of the five sintering approaches is presented in Figure 11. Continuous sintering, followed by HIPing, appears to be the lowest cost route to an acceptable part given the current assumptions.

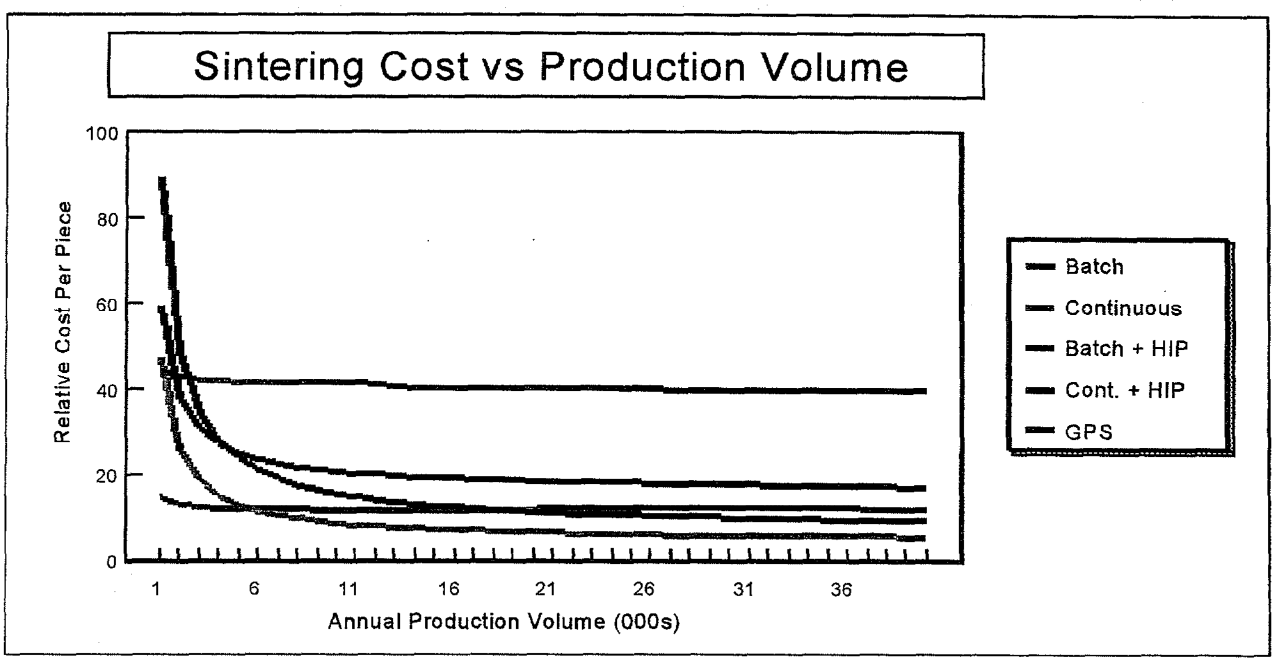


Figure 11. Sintering Cost vs Production Volume

7.2.1.5 Learning and Scaling Improvements.

The changing economics as a result of improvements from learning and economies of scale were examined through applying the model to a number of alternative scenarios reflecting expected production parameters at different points in time. The assumptions for these scenarios are shown in Table 5. Figure 12 shows the reduction in costs with each successive higher-volume scenario. Figure 13 shows the cost plotted on a log scale and the relative contribution of different cost elements by the vertical bars. It is seen that the tooling cost (grinding wheels) is the dominant cost element, so the caveats mentioned in the grinding section must be kept in mind. Figure 14 shows the cost data plotted on a log-log format, and the resulting cost reduction curve approaches the straight line predicted by simplified learning curve models.

Table 5. Various Scenarios for Production Parameters

	1995	1996	1997	1998	1999
Sintering	Batch	Batch	Continuous	Continuous.	Continuous
Powder Formulation	NT451	NT451	NT551	NT551	NT551
Powder Cost ($/kg)	$65.00	$65.00	$35.00	$35.00	$32.00
Grinding Process	Prototype	Junker	Junker	Junker	Junker
Stock Weight (g)	220	175	150	150	110
Forming Yield	95%	95%	97%	97%	97%
Firing Yield	85%	85%	90%	95%	97%
Finishing Yield	80%	80%	95%	95%	99%
Annual Production	200	2,000	10,000	25,000	40,000
Cumulative Production	200	2,200	12,200	37,200	77,200

7.2.1.6 Results and Conclusions.

The valve manufacturing cost model proved to be a valuable tool in assessing the economic impact of alternative process scenarios, in storing process information, and in communicating cost issues to different program team members. With regard to the overall cost, it was no surprise that the highest cost drivers were materials cost, grinding, and sintering. As stated previously, the conclusions drawn were based on projections of a high-volume-production scenario that had not yet been implemented. However, it is clear that the cost and productive lives of grinding wheels have an enormous impact on the grinding and total cost of the valves. Therefore, these grinding-wheel issues must be targeted and better understood in order to assess current costs more accurately and to achieve cost reduction in the future. Under the current assumptions, the model demonstrated the Centerless grinding process (Vendors B and C) to be the low-cost approach for annual production volumes above 4000 valves per year. For volumes between 1000 and 4000 per year, Vendor A's CNC Studer approach was the low-cost approach, and below 1000 per year, Vendor D had a slight advantage. If the assumptions for continuous sintering hold true, then continuous sintering followed by HIPing offers the improvement analysis showed that significant cost reduction will be achieved through volume pricing of material, improved process design, and improved yields. The amount of improvement in cost appears to be two orders of magnitude if total cost, including fixed costs, is taken into account.

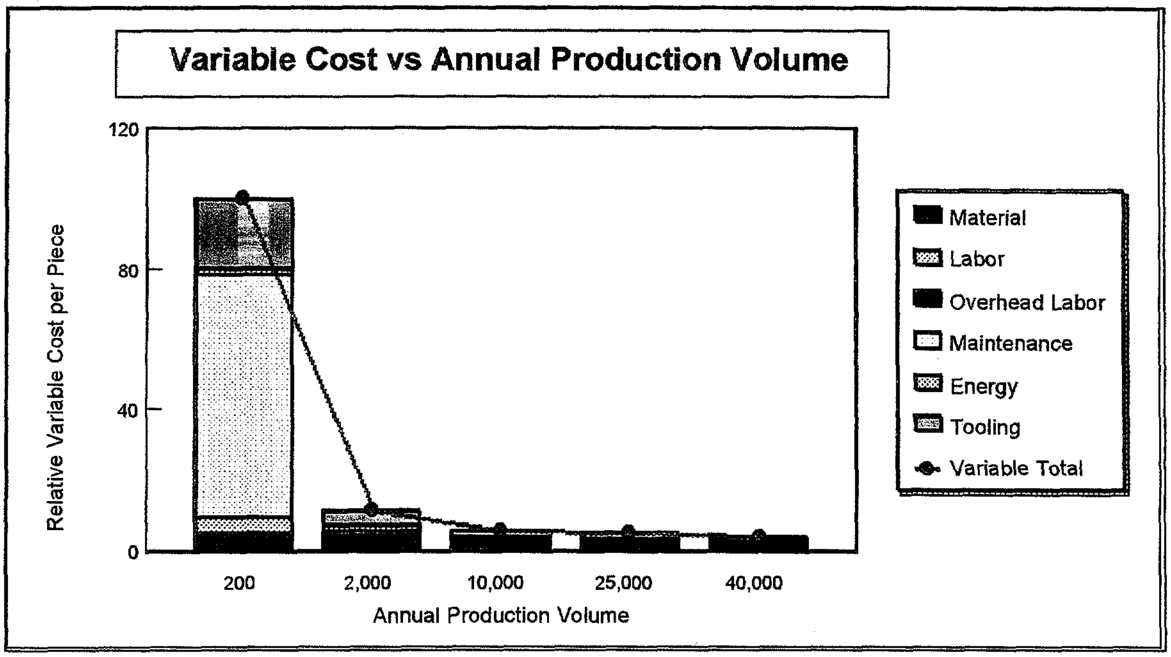


Figure 12. Variable Cost vs Annual Production Volume

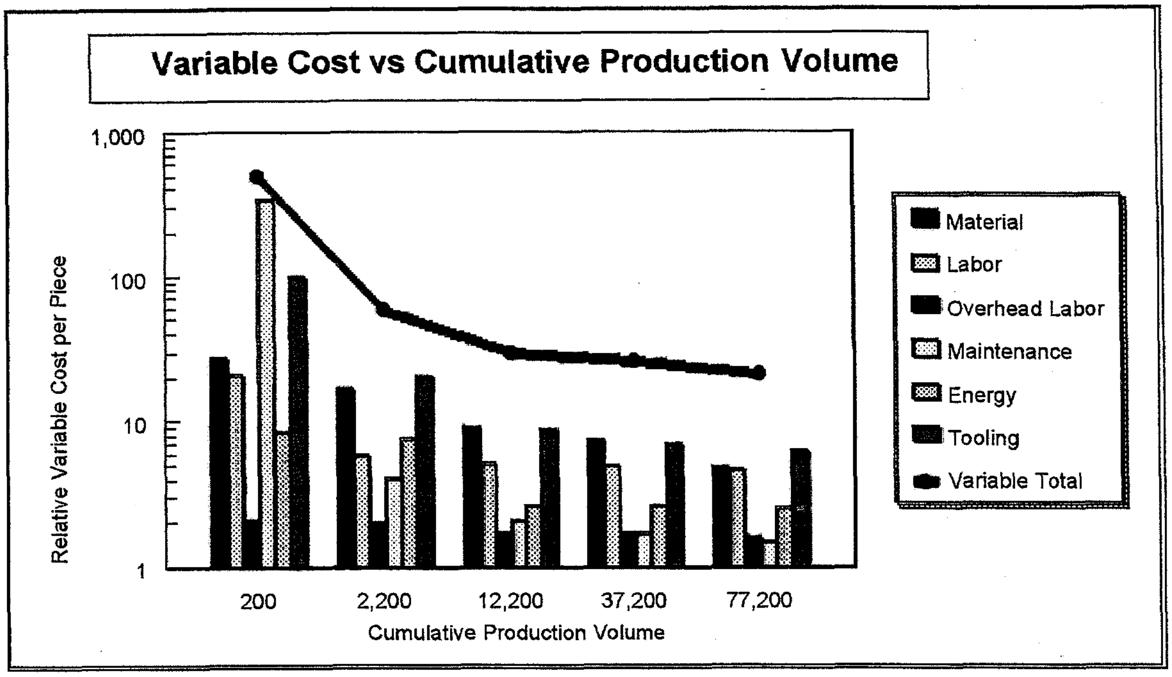


Figure 13. Variable Cost vs Cumulative Production Volume

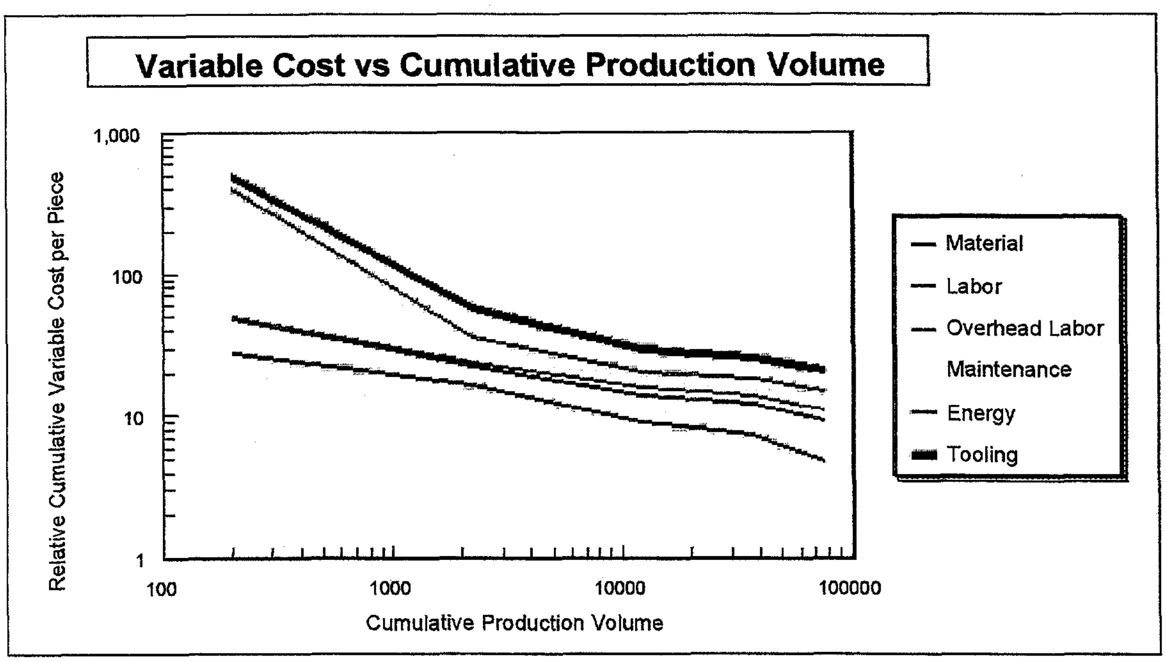


Figure 14. Variable Cost vs Cumulative Production Volume

7.2.2 Environmental Safety and Health - Task 2b

7.2.2.1 Overview.

The manufacture and machining of the silicon nitride engine components does not present an increased risk of injury or illness over traditional metal manufacturing and finishing operations.

Health concerns center around the operator's exposure to hazardous chemicals. The primary constituent in the ceramic is silicon nitride powder, which is non-combustible, non-toxic, and is considered a nuisance dust. Chemical additives include low-molecular-weight binders and antifoaming agents that are relatively non-toxic.

Fine particulates may become airborne during the milling and machining operations. As with any airborne particulate, measures are taken to minimize the inhalation of the dust. Local exhaust ventilation and good housekeeping practices maintain dust levels at a concentration well below the occupational exposure limits. Pyrolysis products generated during the furnace operation are vented out of the building.

Chemical protective gloves minimize the operator's contact with cutting oils, coolants, and dye penetrants that may result in contact dermatitis.

Safety concerns encompass factors that may physically harm the operators. Operators are required to wear safety glasses and safety shoes. Chemical protective gloves are selected based on their compatibility with the materials. Hot pieces are handled with heat protective gloves.

A ceramic component may fail catastrophically during a machining process. This may result in ceramic pieces being projected from the machine. Therefore, it is imperative that the machine have barriers or enclosures to deflect the projectiles. The enclosures are interlocked to prevent accidental access while the machine is running. The operators wear safety glasses with side shields to protect the eyes.

The ceramic components are formed in an isostatic press under great pressures (30,000 psi). The press is periodically (annually) inspected and dye checked according to manufacture recommendations.

The risk of fire or explosion is substantially reduced in that the powder is non-combustible and is milled in water.

The ceramic manufacturing process does not generate hazardous waste as defined by the Resource Conservation and Recovery Act (RCRA). The dry silicon nitride powder is suitable for landfill disposal. Machine oils and coolants are regulated at the state level and handled according to state waste disposal regulations and guidelines.

Particulate emissions are controlled by a dust collection system that provides a greater than 99.999% collection efficiency at a 0.5-micron particle size. During the sintering process, the binder is pyrolyzed. Partial pyrolysis occurs while the furnace is ramping up to the final operating temperature, at which point the binders are pyrolyzed to carbon dioxide and water vapor. The products of incomplete combustion are absorbed in the vacuum pump oil.

Waste water discharges are limited to the dye penetrant used in the inspection process. The dye is a water-soluble oil that is sufficiently removed from the waste stream via a cross-flow hollow-fiber filtration system.

7.2.2.2 Health Considerations.

The following provides a discussion of health-related issues for each major step of the manufacturing process. The discussion focuses on the operator's exposure to chemical hazards.

Powder Preparation. The silicon nitride powder is classified as a non-toxic nuisance dust. The binders and antifoaming agents are rated as low-hazard materials. The generation of airborne dust is controlled by following good handling practices and housekeeping. The low generation rate of material has not warranted the need for local exhaust ventilation or the requirement to wear respiratory protection. Employees are encouraged, but not required, to wear a dust mask and chemical protective gloves when handling the fine powder.

Dry-Bag Isopressing. The operator does not contact any hazardous material during this process.

Green Machining. The green machining operation is conducted in an enclosed CNC machine that is equipped with local exhaust ventilation and dust collection. Operator exposure to airborne dust is maintained at levels well below the occupational exposure limit.

Sintering. The sintering process is conducted in a vacuum furnace where the pyrolysis products are vented out of the building. The operator is not exposed to any hazardous chemicals.

Grinding. The grinding operation is a wet-grinding method where a coolant is applied to the piece. The water-soluble coolant is changed at regular intervals to prevent bacterial growth and accumulation of solids. Mist collectors keep the aerosol concentration well below the occupational exposure limits and the manufacturer's recommended exposure concentrations. Employees are provided chemical protective gloves and long-sleeve uniforms to prevent skin contact that may result in contact dermatitis.

Inspection. The parts are immersed in a dye-penetrant oil (Zyglo 35B). Chemical protective gloves and aprons are provided to prevent contact with the dye.

Oxidation. This is a furnace operation that does not expose the operator to hazardous chemicals.

Packaging and Shipping. This process includes no exposure to hazardous chemicals.

7.2.2.3 Safety Considerations.

The following provides an assessment of safety-related issues for each major manufacturing process. The discussion of safety issues focuses on factors that may physically harm the operator such as fire, explosion, and machine related hazards.

Powder Preparation. The powder is processed in a non-combustible water slurry. There are no flammable agents present. The dry powder does not pose a combustion hazard. The spray dryer is operated at a temperature lower than the decomposition temperature of the binder.

Dry-Bag Isopressing. A concern for the isopress is catastrophic failure of the high-pressure system. The unit is inspected and tested annually in accordance with the manufacturer's recommendations. The unit has several interlocks to assure that all doors and rams are secured before the system is pressurized. Fail-safe pressure-release devices are in place. The operator is shielded from the pressure-delivery system and pressure-release devices by a substantial metal barrier.

Green Machining. The machining of the green parts is performed in a CNC machine equipped with an interlocked enclosure. Therefore, the operator is protected from any projectiles resulting from a catastrophic part failure.

Sintering. Procedures dictate that operators will not open the furnace while operating at elevated temperatures. The product is allowed to cool before handling.

Grinding. The machines are equipped with barriers or interlock guards to protect the operator from projectiles that may result from a part failure.

Inspection. The axial-pull and stem-bend tests are conducted in an enclosure to protect the operator from projectiles.

Oxidation. The operator is provided thermal gloves to protect hands while handling hot objects.

Packaging and Shipping. There are no safety hazards associated with this operation.

7.2.2.4 Environmental Considerations.

The environmental assessment of the process is presented below. All operations, pollution-control equipment, wastes, and emissions are conducted or handled according to state and federal environmental regulations, guidelines, and permit conditions.

Powder Preparation. No waste or emissions are generated by this process.

Dry-Bag Isopressing. Maintenance procedures of the press require the periodic disposal of hydraulic oil. The oil is managed and disposed of in accordance with state waste-management regulations.

Green Machining. Maintenance procedures require the periodic disposal of cutting oils, lubricating oils, and coolant. These materials are handled and disposed of in accordance with state waste-management regulations.

Dust collect fines are not classified as RCRA hazardous waste or state-regulated waste. The dust is acceptable for landfill disposal. The dust collector provides a collection efficiency of 99.999 percent collection efficiency at a 0.5 micron particle size.

Sintering. The binder is pyrolyzed during the sintering process. The majority of the binder is transformed to carbon dioxide and water vapor. Partially pyrolyzed binder emissions are absorbed into the vacuum pump oil or emitted through the stack. The waste pump oil is handled and disposed of as state-regulated oily waste.

Grinding. Coolant aerosols are controlled by mist collectors that return the coolant to the operation.

Inspection. The ceramic parts are inspected via a dye-penetrant system. The dye is a water-soluble oil that is sufficiently removed from the waste stream via a cross-flow hollow-fiber filtration system. The water is discharged to the municipal waste water treatment plant.

Oxidation. There are no environmental impacts associated with this process.

Packaging and Shipping. There are no environmental impacts associated with this process.

7.2.3 Process Control - Task 2c

7.2.3.1 Milling and Spray Drying Process Control - Task 2c.i

In this subtask, NAC directed efforts toward optimizing the milling and spray-drying process steps, using low-cost raw materials and the alternate lower cost silicon nitride designated as NT551. As a part of the cost-reduction effort, NT451 (SiAlON) was replaced by NT551 silicon nitride immediately after the fabrication of 200 SiAlON valves, which were used to establish a base line cost model. The NT551 silicon nitride contributed to the cost reduction effort through (a) use of lower-cost raw powder, (b) process simplification, (c) improved dimensional control, and (d) improved reliability through enhanced fracture toughness. The complete database for NT551 is shown in Table 6 and Figure 15. Two batches of NT551 silicon nitride slurry were prepared using NAC's high-energy attrition mill to: (1) examine the effects of slurry formulation and processing on spray-dried granule properties, and (2) support the development of the spray-drying intelligent control system (ICS). One batch was prepared using a control treatment (Milling Treatment No. 1), while the second batch was prepared using a novel processing technique aimed at producing uniform shape and size agglomerates that "crush" easily during isostatic pressing (Milling Treatment No. 2).

Table 6. NT551 Physical and Mechanical Properties

PROPERTIES	VALUES
Density (g/cc)	**3.285 - 3.290**
22°C Elastic Modulus (GPa)	**302 - 310**
22°C Shear Modulus (GPa)	**118 - 120**
22°C Poisson's Ratio	**.275 - .280**
22°C Hardness (GPa) at 10 kg load	**13.4 - 14.2**
Porosity	**$< 20\ \mu m$**
22°C Mechanical Properties	
⇒ **Flexural Strength (MPa)**	**966**
⇒ **Characteristics Strength (MPa)**	**985**
⇒ **Weibull Modulus**	**20 - 30**
⇒ **Fracture Toughness (MPa$\sqrt{m}$)**	**7.01**
850°C Mechanical Properties	
⇒ **Flexural Strength (MPa)**	**932**
⇒ **Weibull Modulus**	**> 20**

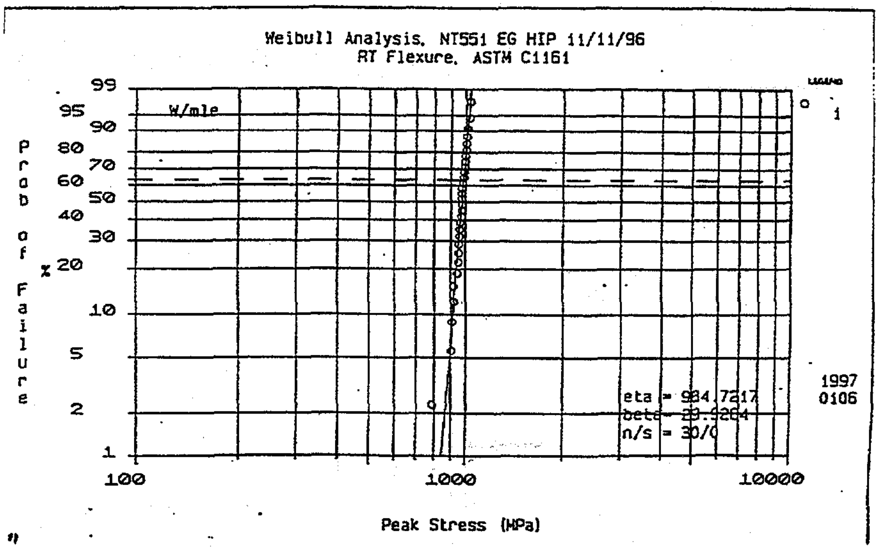


Figure 15. Weibull Analysis

Slurry from each of the two milling treatments was spray dried over a relatively narrow range of spray-drying conditions. The spray-dried powder from the two milling treatments was characterized as part of the milling and spray drying process-control activity. Characteristics of the spray-dried powder from each treatment appeared to be independent of spray-drying conditions. However, as summarized in Table 7, loose packing density, spray-dried-powder moisture content, and agglomerate shape were found to be significantly different between the two treatments. Figure 16 and Figure 17 provide an illustration of the difference in the shape of the spray-dried agglomerates. Milling Treatment No. 2 produced more ideally spherical-shaped agglomerates (i.e., no dimpled or donut-shaped particles) than did Milling Treatment No. 1. Valve blank dry bag pressing trials were made to assess the pressability of these two powders. The fracture surfaces of CIP'ed valve blanks made from spray-dried powder from Milling Treatment No. 2 show no undesirable granular relics. Pressure versus density relationships of CIP'ed powder compacts were also established to support the dry bag isopressing modeling effort.

Table 7. Summary of Characteristics of Spray Dried Powder from Milling Paired-Comparison Experiment

Milling Treatment	Loose Packing Density (g/cc)	Powder Flowability by Hall Flow Meter (sec/25cc)	Moisture Content (w%)	Average Particle Size Distribution (D50)	Qualitative Assessment of Agglomerate Shape
1	1.97 ± 0.02	41.5 ± 2.3	1.38 ± 1.29	79.4 ± 12.1	Dimple Spheres
2	1.73 ± 0.01	40.9 ± 2.7	1.56 ± 1.25	80.2 ± 5.9	Spheres

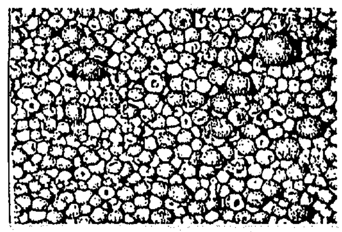


Figure 16. Photograph of Spray-Dried Powder from Milling Treatment - No. 1

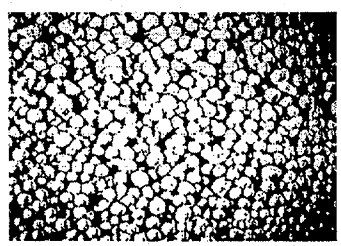


Figure 17. Photograph of Spray-Dried Powder from Milling Treatment - No. 2

A matrix of experiments (L8) was performed to further optimize and fine tune the spray-dried granule properties of the NT551 (fixed) composition. Flowability, pressability, sinterability (both batch and continuous), and the resultant mechanical properties were examined with respect to dispersant and surfactant types and levels. The most significant results obtained from these sets of experiments as a part of the optimized process are summarized in Table 8. The following salient conclusions may be drawn from the resultant sintered properties:

- The slurry chemistry has been optimized yielding consistent batch-sintered densities ≥ 99.4% T.D. (551-10, 14, 15, 17, 21).
- The mechanical properties of batch-sintered NT551 meet DDC's material specifications (551-10, 15, 17).
- The dominant failure origins of the batch-sintered NT551 are relics (residual porosity from spray dried granules).
- NT551 tiles from these batches did not reach a density greater than 99% T.D. (551-11, 16) in continuous sintering. Powder produced from Milling Treatment No. 2 consistently produced higher density during continuous sintering.
- Post HIP treatment following continuous sintering yields full density and significant improvement in mechanical properties and, consequently, in reliability (551-12B). Similar results (not shown) are also realized from batch-sintered, HIP-treated NT551 material.
- Based on these key experiments, the slurry-chemistry, the spray-drying, and the sintering procedures for the NT551 material were defined and a

standard operating procedure (S.O.P.) for the total process was established. As mentioned in 7.2.1 (Task 2a), the cost models for the alternative sintering procedures (i.e., continuous versus continuous plus HIP) were developed by IBIS to establish cost-versus-performance comparisons.

Table 8. Summary of NT551 Properties

			ROOM TEMPERATURE FLEXURE STRENGTH			
POWDER BATCH	SINTERING CONDITIONS	DENSITY (%T.D.)	FRACTURE TOUGHNESS (MPa√m)	AVG. MOR (MPa)	B1 MOR (MPa)	WEIBULL MODULUS
551-10	Batch	99.4	6.7	797	648	19.6
551-11	Continuous	99.2	NM	NM	NM	NM
551-12B	Continuous Sinter + HIP	99.99	6.4	940	757	18.6
551-14	Batch	99.4	6.5	751	565	14.0
551-15	Batch	99.5	6.5	753	640	24.8
551-16	Continuous	97.4	NM	NM	NM	NM
551-17B	Batch	99.7	7.5	740	636	26.6
551-21	Batch	99.7	NM	NM	NM	NM

As part of the optimization effort, the NT551 silicon nitride composition was processed utilizing the established S.O.P., and was subsequently densified following the sinter/HIP approach. The specimens were first sintered in a batch (NAC) or continuous (Centorr/Vacuum Industries/Wittmer Consultants) mode, and were subsequently HIP'ed to achieve densities $\geq$99.9% T.D. The salient mechanical properties corresponding to these two densification approaches are summarized in Table 9. It is obvious from the Table 9 data that, for both those conditions, the mechanical properties obtained meet and/or exceed the targeted values established by DDC.

Table 9. Mechanical Properties of NT551 Silicon Nitride

Densification Procedure	Mean Strength (MPa)	B1 (MPa)	Weibull Modulus, m	K_{IC}* (MPa√m)	No. of Specimens
Batch + Sinter Hip	890	732	22	7.1	20
Continuous Sinter + Hip	970	866	36	7.4	10

Following the above procedures, a substantially larger quantity of specimens (75 tiles and 200 rods) was fabricated and delivered to ORNL. ORNL subsequently generated a flexure and tensile-strength data base from these specimens to establish a life-prediction model for the valves in the diesel-engine environment. This data was reported separately as a part an internal ORNL report.

Using the sinter/HIP approach, a set of valves was densified and their straightness (TIR) was measured. As compared to sintered SiAlON (NT451), a factor of 3 reduction in bending was achieved with NT551 silicon nitride. Decreased bending (TIR) reduces the machining time/cost significantly, thus further contributing to the ultimate goal of cost reduction.

A large quantity of NT551 valves was fabricated and delivered to Vendors A, C, and D in support of valve machining optimization.

7.2.3.2 Continuous Sintering - Task 2c.ii

The purpose of this subtask was to investigate the potential for cost-effective sintering of silicon nitride exhaust valves through the development of continuous-sintering techniques for NAC's NT451 (base line) and NT551 silicon nitride materials.

The continuous-sintered properties of NT451 and NT551 were equal to or better than those measured for NT451 and NT551 sintered by NAC in the batch furnace.

The potential throughput for valves by continuous sintering has been demonstrated, and the cost analysis for sintering valves by continuous sintering is favorable.

Texturing of the sintering bed has improved the total indicated runout (TIR) by over 50% but further improvements are desired. It is recognized that improvements in TIR could be realized by vertical orientation during sintering.

Improvement in the texturing of the sintering bed for sintering valves in the horizontal orientation, along with improvements in the green density gradients in the as-formed valve blanks, are areas for future pursuit.

Raw Material Process Control.

Continuous Sintering Screening. The objective of this task was to evaluate NT451 SiAlON prepared from five commercially available silicon nitride powders. In parallel with batch sintering conducted by NAC, specimens from the same NT451 batches were continuously sintered in the Model 6-BF belt furnace at Centorr/Vacuum Industries, Inc. (CVI). Initial sintering trials contained NT451 tiles processed from three of the five silicon nitride powders, and subsequent sintering trials contained NT451, in the form of short rods, processed with all five silicon nitride powders. The continuous-sintering parameters investigated were sintering temperature and sintering time. Following continuous sintering, the weight loss and density were measured and recorded, and then the specimens were returned to NAC for property and microstructural evaluation.

In the initial trial, fifteen test billets of NT451 made from three of five silicon nitride powders were sintered in CVI's Model 6-BF belt furnace under four different time/temperature conditions. The sintering conditions and density results are given in Appendix A, Table I. These results indicate that NT451 made from SLX-15 and SLX-19 could be continuously sintered to greater than 99% of theoretical density for the sintering conditions chosen. The SLX version of NT451 (SiAlON) represents use of low cost raw silicon nitride powder.

Following the initial trials, cylindrical specimens of NT451 processed from each of the five silicon nitride powders were also processed and continuously sintered. Five continuous-sintering runs were completed for three sintering times and two sintering temperatures. The sintering results given in Appendix A, Table II show once again that NT451 made from SLX-15 and SLX-19 could be continuously sintered to greater than 99% of the target density, while the other three silicon nitride powders produced less than 99% of the target density.

Dimensional Control. The goal of this task was to determine the effect of furnace conditions and specimen orientation on sintering uniformity and specimen warpage. Initially, valves were sectioned and continuously sintered in the Model 6-BF belt furnace at CVI. Based on these results, preferred sintering conditions were determined and furnace fixturing was designed for continuous sintering of full-sized, whole valves by Wittmer Consultants in the Model 44-BF belt furnace at Southern Illinois University-Carbondale (SIU-C).

Initially, rigid fixtures were designed which could support the length of the valve in a V-cradle. The angles of the V-cradle were designed to allow the head and shaft of the valve to be supported while the valve shrank during densification. Since the heating was from either the head or shaft end of the valve, the rate of shrinkage was not constant. This fixture allowed the valve to distort perpendicular to the V-cradle.

A non-rigid fixture was required in order to support the entire length of the valve during shrinkage and densification. The concept of using a flowable sintering bed of powder, coarse enough so that it would not pack around the valve, was investigated. This procedure was used to produce valves with warpage comparable to that of those sintered in batch operations by NAC. All full-sized valves for this program were sintered in the continuous furnace by this method.

In order to improve the sintering production rate, two full-sized valves were stacked in the flowable bed with a marginal space between the two valves. This technique appeared to work well, depending on whether or not the valves made contact during sintering. Larger boats would eliminate this problem and make it possible to sinter at least four valves per boat, giving four times the production rate of the current practice.

Also, an attempt was made to determine whether the orientation of the valve as it entered the continuous furnace (head or tail first) had a measurable effect on the valve warpage during sintering. Based on limited data, the valve orientation does not appear to be an issue with regard to warpage.

To determine warpage of the NT451 valve shaft during sintering, two valve shafts were measured before and after continuous sintering. Prior to sintering, the valves were placed in a lathe and the runout measured by use of a dial indicator with 0.00254-mm (0.0001-in.) precision. The green shafts were found to be true to less than 0.00254 mm (0.0001 in.) and to have a less than 0.0127-mm (0.00005-in.) taper over the full length. While in the lathe, the shafts were indexed at 2.54-cm (1-in.) intervals over the length. The valve head was then removed, and the shaft sintered. Following sintering at T4 for a time of t3, the runout was measured on the two sections and was found to be approximately 0.914 mm (0.036 in.) over the length of the shaft.

As a result of discussions with NAC concerning the mixed results for valve-shaft warpage, it was learned that a presintering treatment was most likely responsible for the variable warpage observed. It was believed that density gradients in the green parts over the valve cross-section and length were due to the machining of isopressed valves off-axis of the centerline. This off-axis alignment would then cause the valve to warp in the direction of the greatest shrinkage. Following further discussion on this subject, it was proposed that CAT (computer aided tomography) analyses be used to help verify the probable cause.

Two green exhaust valves from the first-two-received lots of NT451 were submitted to ORNL for CAT analyses. These analyses were performed to determine if the technique were capable of detecting density gradients and/or microstructural features which cause warpage during sintering. It was hoped that process improvements would reduce density gradients in the valves prior to sintering, which would reduce warpage. The valves were indexed along the length of the valve using a line laser, and scans were made of the valve cross-section at each index. The valves were physically scribed to allow CAT scans at the same locations following sintering. Some pore clustering and minor density variations were observed within each of the scans. Both of the valves were continuously sintered in the Model 44-BF belt furnace with the tungsten hot zone installed. The preliminary results indicated the presence of density gradients in the valve stem in the location near the greatest warpage. This would indicate that there are potential density gradients in the green valve, as suspected. Process improvements in obtaining a more-free-flowing powder and an isopress bag designed to produce a more-uniform pressure distribution should aid in the minimization of these density gradients. Improved packing-density uniformity in the CIP bag for the valve was accomplished through an Intelligent Processing approach developed jointly with BDM Federal, Inc./MATSYS, Inc. As described in Section 7.2.4, the density gradient in the valve was significantly reduced with the help of the Intelligent Control Spray Drying methodology and Finite Element Modeling of the valve isopressing process.

A few valves that were continuously sintered met the specification for runout and were machined to specification by NAC.

At this point, based on compositional work conducted by NAC in an internal program, the project plan was modified to include NT551, a new, lower-cost composition. It was also decided to make a comparison of continuous and batch sintering with respect to warpage for the same powder lots.

Continuous Sintering Optimization. Sintering optimization was performed using NT551 valves. A major goal of this task was to compare the results obtained with the belt furnace operating at steady state with the results obtained for the shorter, non-steady state trials.

Approximately 100 pieces of NT551 were continuously sintered in eight runs primarily to evaluate: (a) lower-cost silicon nitride raw materials, and/or (b) the powder processing methodology of milling and spray drying. Sintering to closed porosity was accomplished by continuous sintering for several of the test conditions; however, it appeared that additional surface decomposition may have produced lower density than anticipated. Nineteen additional continuous sintering runs were made under a range of time/temperature/belt speed conditions. Several billets and a few valves of NT551 powder processed under three different conditions were continuously sintered during these runs. These results demonstrated that there is a high degree of sensitivity of sintered density to processing and sintering conditions. Sintering to closed porosity was accomplished by continuous sintering for several of the test conditions, and density equivalent or nearly equivalent to that of conventional batch sintering was obtained. Based on these results, NAC selected a formulation and processing condition for the NT551 to complete the program.

Appendix A, Table III gives the continuous sintering results for the preliminary NT551 formulation and processing condition. The coded data show that a density of 3.26 g/cc was obtained for three Temperature/time (T/t) conditions (5/4, 4/4, and 4/3) of the twelve T/t sintering conditions run. These results represent 98-99% of the target density desired.

The results given in Appendix A, Table IV are the density data for two sintering time/Temperature conditions (t4/T5 and t3/T5) for both billets and valves that represented three processing/formulation variations (10, 11, and 12). Two different belt speeds (3 and 4) were used in conjunction with two hot zone configurations to provide two heating rates for the same t/T conditions. These results show that none of the processing/formulation variations produced high density, and that there were significant differences in the densities obtained for the variations in thermal conditions. Composition 12 produced the highest density in both billet and valve forms.

Run 51 data (Appendix A, Table V) show that at a Temperature/time code of 7/2, the billets all exhibited significant silicon formation on the surfaces and/or edges. At all other conditions (Runs 52 through 55 and Run 62, Tables VI through XI, respectively) variations in density with processing/formulation variations were observed. The densities ranged from about 92 to 99% of the theoretical target densities provided by NAC. Run 62 (Appendix A, Tables X and XI) was a repeat of Run 53 for Lot ND2-22 and Lot ND2-16. Additional sintering trials were made with tiles, rods, pellets, and valves for Runs 66, 80, 85, and 86 (Appendix A, Tables XII through XIX).

Based on NAC results obtained from post-sintered/HIPed trials, NAC targeted ND2-16 as the composition (raw material) and the processing route for the completion of this program. The conditions of temperature T5 and continuous sintering time of t4 were selected as the optimum sintering conditions for this formulation, and were used for the pilot scale sintering runs.

Following HIPing, physical properties were compared for both the NAC batch-sintered NT551 and the continuous-sintered NT551 (Table 7 on Page 30). The mean strength of the continuous-sintered NT551 was about 9% higher than the batch-sintered material from the same lot of NT551 powder. Also the Weibull Modulus was increased by almost 64% for the continuous-sintered/HIPed NT551, and the fracture toughness was improved by about 4% over the batch-sintered/HIPed NT551. According to NAC and as predicted by previous cost analyses, it would appear that the cost of continuous sintering of the exhaust valve is about 50% the cost of batch sintering alone, while the cost of continuous sinter/HIP is about 75% the cost of batch sintering alone. Therefore, continuous sintering offers both a physical property advantage and cost advantage, even if HIPing is required to improve the strength/reliability factor.

Continuous Furnace Design Study for Silicon Nitride Exhaust Valves.

The goal of this task was to design and specify a furnace capable of continuously sintering exhaust valves cost effectively. It has been reasonably demonstrated that continuous sintering can be used to produce NT451 or NT551 exhaust valves which meet density and surface-reaction-layer specifications. Also, with horizontal fixturing, it has been demonstrated that relatively straight valves can be horizontally sintered to full density, if the presintered form is free of significant density gradients. However, based on the current results obtained for horizontal fixturing, using the present presintered form, it is unlikely that horizontal fixturing will allow the economic production of valves which meet the criteria for stem warpage and meet the cost projections for the volume of valves anticipated. In order to economically sinter exhaust valves continuously in the horizontal position, more grind stock or presintering process improvements will most likely be necessary.

The lowest-risk approach was to consider continuously sintering valves only in the vertical position. This procedure has been demonstrated in the present Model 44-BF belt furnace only for shortened valves suspended in vertical fixturing. However, it is believed that there are no technical barriers to successfully sintering full-sized valves continuously, given a properly designed hot-zone and fixturing system. Both horizontal and vertical valve orientations were considered for the design of the furnace(s) as part of the deliverable for this task.

The design for a continuous sintering furnace capable of sintering 30,000 valves per year was completed. The furnace load cross section is 6 in. by 12 in., the hot zone contains three zones heated by graphite elements, and the belt is SiC link. A 300 KVA transformer would be required to fully power this furnace to a maximum design temperature of 2200° C.

Demonstration of Continuous Sintering of NT551 Exhaust Valves.

Two extended continuous-sintering runs at a temperature of T5 and for a time of t4 were made to demonstrate pilot-production capability of continuous sintering for NT551. Only one valve was sintered per boat, with the valve orientation headfirst, and the boats with valves weighted the same (2500 g). The first run (Run 100, Appendix A, Tables XX, XXI and XXII) was a preliminary run containing 38 valves from Powder Lot 7. The final run (Run 105, Appendix A, Tables XXIII through XXVI) contained 66 valves (46 valves from Powder Lot 17, and 20 valves from Powder Lot 18). Both the valve ID and the order in the sintering train were recorded.

As seen from the preliminary results, roughly half of the valves were sintered without cracking or severe warpage. The data for these valves are given in Appendix A, Table XX. The weight loss was about 1%, and the sintered densities were all over 98% of the target. Although these valves appear to be well within the acceptable limits for distortion and were free of cracking, there appears to be some question about multi-directional warpage in the "good" valves. On average, the total indicated runout (TIR) of the continuously sintered valves was about a factor of 2 higher than that of those sintered in a batch furnace.

The results for the remainder of the sintered valves are given in Appendix A, Tables XXI and XXII. As seen from these results, either these valves were damaged prior to sintering or their heads cracked during sintering. The lack of any correlation of the crack orientation with respect to the valve orientation during sintering would indicate that orientation of the valve was not responsible for the valve cracking. However, all of the valves that showed presintered damage cracked during sintering. This may indicate a problem with green density gradients or subsurface machining damage in the green machined valves.

The results for the final continuous sintering run are given in Appendix A, Table XXIII through XXVI. Sixty-six valves from two different lots of NT551 (46 from Lot 17 and 20 from Lot 18) were continuously sintered at a temperature of T5 and for a time of t4. Three of the green valves broke during shipment, and four of the remaining sixty-six cracked during sintering. The remaining sixty-two valves appeared to be crack free, and nearly all of them sintered to >98% of the target density. There did not appear to be any significant warpage on more than a few of these valves. The TIR NAC reported was very similar to that observed for the batch-sintered valves from the same lots of powder.

The ability to continuously sinter full-sized Series 149 exhaust valves successfully in the horizontal position has been demonstrated, and can be improved only through a vertical arrangement. It is believed that improvements in the powder packing during the initial valve blank preparation will reduce the green density gradients responsible for the large variation in TIR noted in both batch- and continuous-sintered valves.

In preparation for the final demonstration of the valve-manufacture process, the S.O.P. for both the batch- and the continuous-sintering processes were defined and documented.

A sufficient quantity of batch, as well as continuously sintered NT551 valves, followed by HIP, were also evaluated for dimensional control (TIR). Overall, the batch-sintered valves showed better dimensional control (Figure 18). This is not unexpected, as during the continuous-sintering process, valves were not fixtured in an optimal configuration due to the limitations of the current furnace-chamber design. It is essential to emphasize here that the dimensional control is an extremely important factor in efficient machining and overall process yield.

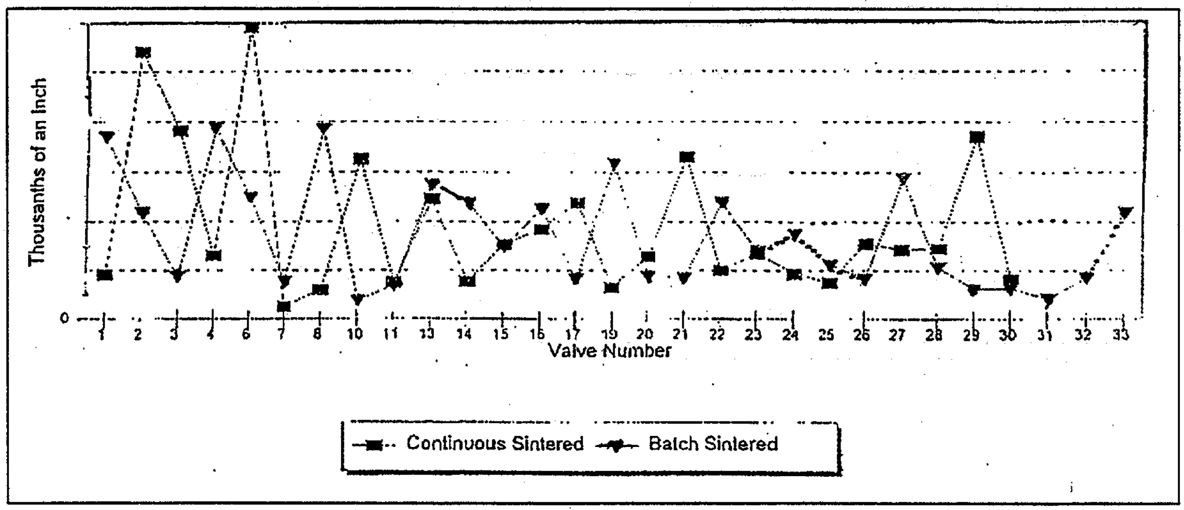


Figure 18. Valve Bending in Continuous vs Batch Sintering

7.2.3.3 Machining - Task 2c.iii

The cost-effective machining process for the DDC Series 149 Engine silicon nitride valve was developed by NAC in collaboration with Vendor A (Norton Company, Higgins Grinding Technology Center). Vendor A helped to develop two potentially cost-effective machining procedures: Centerless Plunge Grinding in conjunction with Vendor B (Deco-Grand, Inc.); and CNC Profile Grinding at Vendor A's facility in conjunction with Studer Machine Tool Company. In addition, NAC engaged additional outside facilities to further evaluate two alternate cost-effective machining procedures: Compound Centerless Grinding (Vendor C) and Peel Grinding (Vendor D). The development efforts for each of these machining procedures are described following.

Centerless Plunge Grinding (Vendor B). The valve-grinding process in place at NAC at the outset of this program utilized between-centers grinding of the valve stem and head radius on CNC OD grinders. This method produced high-quality valves but was limited in cost-effectiveness for high-volume production. Vendor A proposed the development, in conjunction with Vendor B, of a cost-effective alternate methodology for the mass production of ceramic valves.

The initial work at the Vendor A facility was focused on the development of a centerless-plunge-grinding approach for grinding the ceramic valve stem and head radius. The optimum wheel specifications for higher productivity and better ceramic surface integrity were established by utilizing existing wheel technologies. Wheel variables, such as bond type, abrasive size, and wheel composition, were investigated at different operating conditions. A simulation centerless grinding test was developed with the equipment at Vendor A's facility. NAC machinists demonstrated the feasibility of centerless plunge grinding on the NAC Tshuden centerless. Finally, the technology, including wheel specifications, production data, and process-control information was transferred to Vendor B's facility for full-size valve production.

Simulation Test Development. As the first step, a centerless-grinding simulation test was developed using a DedTru centerless device mounted on the table of an Elb Super Brilliant surface grinder, as illustrated in Figure 19. The objectives of this simulation were to:

- Screen the various bond technologies (organic, vitrified, and MSL).
- Determine the achievable material-removal rates (MRR).
- Monitor the various parameters (forces, power, surface finish, wheel wear) pertaining to the process.
- Make recommendations for a subsequent, scaled-up centerless test.

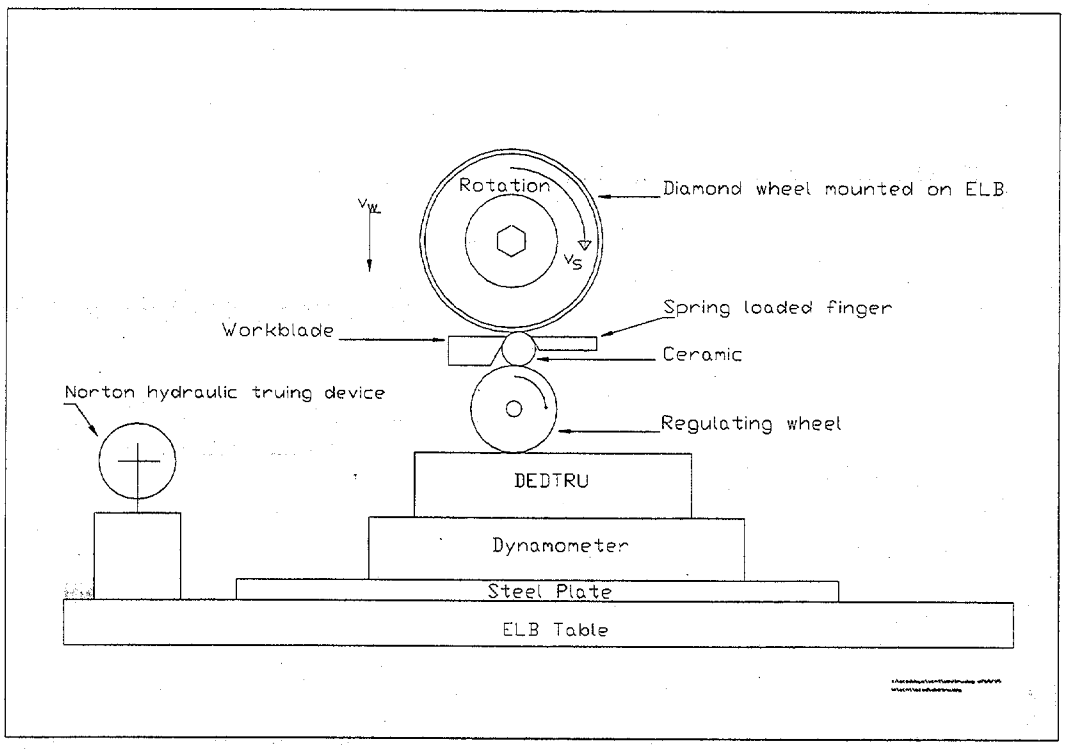


Figure 19. Centerless Grinding Simulation

Serialized SiAlON valves were provided to Vendor A, which cut each 6.5-in.-long stem into thirteen 0.450-in.-long sections. These sections were placed into separate containers to allow for future tracking.

The following wheels were evaluated in the test:

- Three organic wheels:
  - SD 320 R100 B619 C
  - SD 320 R100 B80
  - D 10/20μ R100 BX619 C

- Nine vitrified bond wheels (in two concentrations, 100 and 150; two grit sizes, 320 and10/20μm; and four grades, K, N, P, and R):
  - SD 320 N6 V10
  - SD 320 P6 V10
  - SD 320 R6 V10
  - SD 320 N4 V10
  - SD 320 P4 V10
  - SD 320 R4 V10
  - D 10/20μ N6 V10
  - D 10/20μ P6 V10
  - D 10/20μ K6 V10
- One MSL wheel:
  - D 170/200 H MSL

The simulation test was broken down into the following five phases: (1) test-method development; (2) 320-grit rough grinding; (3) 320-grit, extended duration test; (4) 10/20-μm finish grind; and (5) 10/20-μm extended grinding.

Examples of the simulation test data gathered are presented in Table 10, Table 11, andTable 12. Following each of the three tables are explanations of the type data collected and of the terminology used in this portion of the report.

Table 10. Centerless Grinding Simulation Test Data (1)

Run #	Feed Rate	Workpiece Diameter Initial	Workpiece Diameter Final	Material Removed (diam)	Grinding Time	MRR'	MRR'
	mm/min	in.	in.	in.	s	in.^{3}/min/in.	mm^3/s/mm
1	10	0.4270	0.3370	0.0900	11.66	0.278	2.987
2	10	0.4270	0.3431	0.0839	11.66	0.261	2.807
3	10	0.4270	0.3420	0.0880	11.66	0.275	2.952
4	10	0.4270	0.3411	0.0879	11.66	0.274	2.941
Summary	**10**	**0.4283**	**0.3408**	**0.0875**	**11.66**	**0.272**	**2.922**

- Run #: An individual piece of ceramic.
- Feed Rate: The rate in millimeters per minute the wheel was fed down on the ceramic.
- Initial, Final, Material Removed: The starting diameter, ending diameter, and total amount of material removed in diameter.
- Grinding Time: The actual total grinding time in seconds (s).
- MRR': The volumetric material removed in unit time with a unit wheel width.
- Summary: The averages from the individual columns.

Table 11. Centerless Grinding Simulation Test Data (2)

	Cumulative Wheel Wear		Surface Finish, Ra	
Run #	in.	mm	µin.	µm
Summary	0.0003	0.00762	22	0.56

- Cumulative Wheel Wear: The wheel wear on the radius in both English and metric units.
- Ra: The roughness average in µin. and micrometers.

Table 12. Centerless Grinding Simulation Test Data (3)

	Power (kW)		Normal Force (lb)		Tangential Force (lb)		G-ratio	Spec. E	Grindability
Run #	Initial	Final	Initial	Final	Initial	Final		kW·min/in.^{3}	in.^{3}/kW·min
1	0.53	0.61	36	32	6	6		2.04	
2	0.83	0.65	36	26	6	5		2.82	
3	0.80	0.55	38	32	6	6		2.46	
4	0.85	0.55	42	24	7	5		2.56	
Summary	**0.83**	**0.58**	**39**	**27**	**6**	**5**	**7.01**	**2.61**	**2.68**

- Power: The initial and final spindle power measured in kW on a flat bed chart recorder.
- Normal Forces: The initial and final vertical forces measured in lb on a flat bed chart recorder.
- Tangential Forces: The initial and final horizontal forces measured in lb on a flat bed chart recorder.
- G-Ratio: Compares the volume of wheel used to the volume of material ground.
- Specific Energy: The average of the initial and final power divided by the MRR.
- Grindability: G-Ratio divided by Specific Energy.

The preliminary testing conditions are listed in Table 13.

Table 13. Centerless Grinding Simulation Test Data (4)

Wheel	Specification:	Listed above
	Size:	8 in. x 1/2 in. x 3 in.
	Speed:	3,818 rpm = 7,996 SFPM = 41 m/s
	Feed Rate:	Varying from 10 to 30 mm/min
Regulating Wheel	Speed:	150 rpm
Workpiece	Speed:	1,515 rpm = 157 SFPM
Truing	Truing Wheel Size:	3.5 in.
	Truing Wheel Speed:	1,993 rpm = 1,826 SFPM
	Wheel Speed:	1,090 rpm = 2,282 SFPM = 10m/s
	Dressing Stick:	NSA400G5V
Coolant:		10% Master Chemical E-200

The following three experiments were conducted. Details of each experiment are provided immediately following.

- Influence of the reaction layer of the workpiece.
- Maximum achievable MRR'.
- Influence of the dressing conditions and extended testing.

Influence of the Reaction Layer. Utilizing the SD 320 R100 B619 C wheel, three parts were ground below the reaction layer [DOC (depth of cut) 0.122 in.] at 10 mm/min. The power and forces were monitored for any changes while grinding through the layers. In addition, Ras were recorded for every part ground. The ceramic specimen was centered on the DedTru regulating wheel and held in place by blades to the left and right, and by fingers on the front and rear, of the part. The wheel was plunged at the pre-programmed rates to a specified DOC. There was a two-second dwell at the end of each run. Power, normal and tangential forces, surface finish, and wheel wear were monitored, and the respective data were documented.

After grinding the three parts well below the reaction layer, the power traces and power charts were analyzed. There was no evidence that the reaction layer created any differences in power or forces that would adversely affect wheel wear.

Maximum Achievable MRR'. The goal of this experiment was to grind at the fastest possible MRR' while maintaining a good G ratio and low power. Each part was measured before and after grinding to determine the material removed. Any difference caused by wheel wear between the target diameter and the actual diameter was compensated for in the controller after each run.

- Ground an average of three parts (DOC 0.0557 in.) at 30 mm/min, which corresponded to a MRR' of 0.743 $in.^3$/min/in.
- Ground an average of three parts (DOC 0.058 in.) at 20 mm/min, which corresponded to a MRR' of 0.501 $in.^3$/min/in.
- Ground an average of three parts (DOC 0.0553 in.) at 10 mm/min, which corresponded to a MRR' of 0.240 $in.^3$/min/in.
- Ground twelve parts (DOC 0.0554 in.) at 30 mm/min, which corresponded to a MRR' of 0.740 $in.^3$/min/in. This test was to confirm that the wheel acts the same on tests of both short and longer duration.

A material removal rate of 0.743 $in.^3$/min/in. (7.5 mm^3/mm/s) was successfully obtained as the maximum MRR on the SiAlON parts. This corresponds to a vertical speed of 30 mm/min. Lower and medium respective values of 10 and 20 mm/min were also evaluated. Such a MRR' has a significant impact on the total cost of the SiAlON valve by dramatically reducing the cycle time needed to rough grind the valves.

Influence of the Dressing Conditions. This experiment was conducted to determine the effects of extended grinding on the wheels and power. Wheels mounted on the machine were balanced, trued, and dressed by hand. After each test the wheel was measured for radial wear using a depth micrometer. The wheel was retrued on a Norton hydraulic rotary truing device with a traverse rate of 10 in./min and a DOC of 50 μin. per pass, and then redressed by the stick. Two tests were conducted at a MRR' of 0.740 $in.^3$/min/in.

No additional dressing beyond the initial one was necessary to keep the wheel face open. In all tests, the power and forces reached a steady state after the first part was ground.

Test Procedures. Each test consisted of plunge grinding four sections of a valve stem to a dimension of two thousandths (0.002 in.) above their finished diameter. The Ra of the last piece was measured on every test. In all cases, the data from the first part ground was recorded but was not used to compute the average power and forces. An attempt was made to grind in the same manner with all wheels but, due to high power and forces, some tests had to be interrupted.

During the centerless grinding simulation at Vendor A's facility, both roughing with 320 grit wheels and finishing with 10/20-µm wheels were explored according to the grinding test procedure described. During this process, the following observations were made:

- The SD 320 R 100 B619C organic-bond wheel drew less power and forces than the SD 320 R100 B80 wheel.
- The SD 320 N6 V10 vitrified-bond wheel was the best of the six wheels tested. It exhibited low power, forces, and a good G ratio.
- The MSL wheel wore quickly and had high power and forces.

Vendor A successfully simulated large-production, through-feed, centerless grinding of ceramics on a small scale, thus avoiding a costly, full-scale production process. A material removal rate of 0.743 in.^{3}/min/in. (7.5 mm^3/mm/s) was successfully obtained, and 0.05 to 0.1-µm surface finishes were achieved.[10]

Scale-up. The various wheel specifications selected in the short and extended tests, and recommended for the 12 in. centerless scale-up are listed below for Operations 20, 40, and 50.

In order to scale up this simulation to allow investigation of the feasibility of centerless plunge grinding at high MRR on a much longer section of the valve stem, the refurbishing of a Vendor A-acquired Super–Tec centerless grinder and the rebuilding of a Norton #3 centerless grinder were attempted. However, both plans to conduct larger-scale centerless grinding trials at Vendor A's facility were abandoned in favor of going directly to full-scale ceramic valve grinding demonstrations at Vendor B's facility. Vendor A's efforts were then redirected toward providing technical assistance to Vendor B on the upgrade of a Lidköping centerless grinding machine.

A total of three full-size vitrified centerless grinding wheels for rough and finish stem, underhead, and head grinding were specified and modified as follows for Vendor B's valve grinding unit operation Nos. 20, 40, and 50.

- For Operation 20
  - Modified Wheel #1:
    - Changed Thickness from 5.5 to 7.25 in.
    - Added 0.5 in. Radius
    - Altered the ID from 6.5 to 9 in.
- For Operation 40
  - Ordered 12 in. x 1 in. x 9 in. SD320N6V10 Wheel Shaped to the Valve Blueprint
- For Operation 50
  - Modified Wheel #2 (Same as Modified Wheel #1)
  - Added a Spacer
  - Added a 1V1 Wheel D10/20P6V10 (Slightly Harder to Compensate for Smaller Diameter).

The balance of the tooling required for ceramic-valve grinding trials, including a rotary diamond wheel dresser, an infeed controller for the Lidköping centerless grinder, and wheel mounts, were specified and ordered. A process routing for centerless grinding Series 149 valves was finalized. After that point, all of the centerless-grinding testing activities were performed at Vendor B's facility.

Vendor A provided product engineering assistance to Vendor B for the successful demonstration of plunge grinding of the stem portions of the valve. After the Lidköping machine was modified and the centerless-grinding technology was established, twenty valves finish machined by Vendor B were inspected for dimensional accuracy. Unfortunately, they did not meet either the dimensional or the surface-finish specifications. Valve pull tests were performed on the Instron Machine using a specially designed fixture and keepers designed and provided by DDC. The finish-machined valves were proof tested in accordance with DDC's specifications, and 6 of the 19 Vendor B valves failed the pull test. In the interim, Vendor B fine tuned the truing procedure in order to improve both the valve dimensions and the surface finish. Because of the limited time and resources available, the centerless-plunge grinding approach was discontinued and efforts were focussed on the CNC Profile Grinding technique described below.

The above negative results do not eliminate centerless grinding as a production-viable process for ceramic components. However, they do emphasize the need for utilizing a systems approach whereby all aspects of the grinding process, i.e. the machine tool, the grinding wheel, the work material, and the operational factors, are optimized simultaneously to achieve the desired grinding results.

It should be noted that, during the same period, an in-parallel project conducted jointly with Vendor A resulted in successful through-feed centerless grinding of ceramic components for a diesel injection fuel system component.[11]

CNC Profile Grinding (Vendor A). In parallel with the centerless-grinding development activity, Vendor A assessed several alternative grinding technologies. After receiving a Studer S40 CNC grinder, the Vendor A explored extensively the viability of high-speed profile grinding as an alternative approach.

A preliminary test successfully demonstrated the feasibility of this approach. The stem, head radius, and seat of 6 valves, mounted between centers on the Studer machine, were rough ground with a diamond MSL wheel rotating at 150 m/s; then finish ground with a 320-grit vitrified bond diamond wheel at conventional speed. The promising grinding-time reductions obtained are presented in Table 14. In addition, all the valves ground met the ±0.0004 in. dimensional tolerance and the surface finish requirement of Ra < 8 μin.

Table 14. Valve CNC Profile Grinding Data (1)

	Current @ NAC	Vendor A (10/1/95)
Rough Stem	10-15 min	6½ min
Rough Head	7-8 min	3 min
Finish Grind	40 min	10 min
Max Total Grinding Time*	63 min	20 min

* Set-up time included unless otherwise specified.

Based on the preliminary demonstration, Studer profile grinding, with its versatility and high-speed capability, was determined to be promising as an emerging technology for the cost-effective batch production of ceramic valves.

CNC Profile Grinding Test, Phase 1. To further improve these already very dramatic cycle-time reductions, two approaches were evaluated: adding a steady rest to the rough profiling setup; and changing the method of holding the part from a non-integral dead center to a precision collet on the head end and a live center on the tip end.

After a steady rest was installed in the original setup of the Studer machine, a higher material removal rate (MRR) was achieved without additional valve deflection during the grinding. As shown in Table 15, despite the addition of a grinding operation for placement of the steady rest, the successful development of the roughing operations resulted in a factor of four grinding time reduction when compared to the NAC prototype process.

Table 15. Valve CNC Profile Grinding Data (2)

	Current @ NAC	**Vendor A (10/1/95 Report)**	**Vendor A (12/1/95 Report)**
Plunge Grind for Steady Rest	–	–	3.9 min
Rough Stem	10-15 min	6½ min	–
Rough Head	7-8 min	3 min	–
Total Rough Grinding Time	*17-23 min*	*9.5 min*	*3.4 min*
Finish Grind	40 min	10 min	10 min
Max Total Grinding Time	63 min	20 min	17.3 min

The part-holding fixtures were then ordered. The modification effectively enhanced the workpiece holding during grinding, and necessitated only minor changes to the design of the fired blanks. Once the valve blanks were redesigned, Vendor A continued work on 30 valves to further optimize the roughing and finishing operations.

It was discovered that, due to the extreme bend in the received blanks after firing, with the previous fixturing the stem portion of the valve did not clean up even if finish grinding were performed, Figure 20 illustrates how this design, combined with the bend in the part, reduced the maximum part size. To solve this very serious issue, the fixturing was modified to shift the axis of rotation of the valve to compensate for a portion of the bending. Figure 21 illustrates how, by shifting the axis of rotation, the maximum part size was increased. Figure 22 shows a manual method for identifying the bend direction.

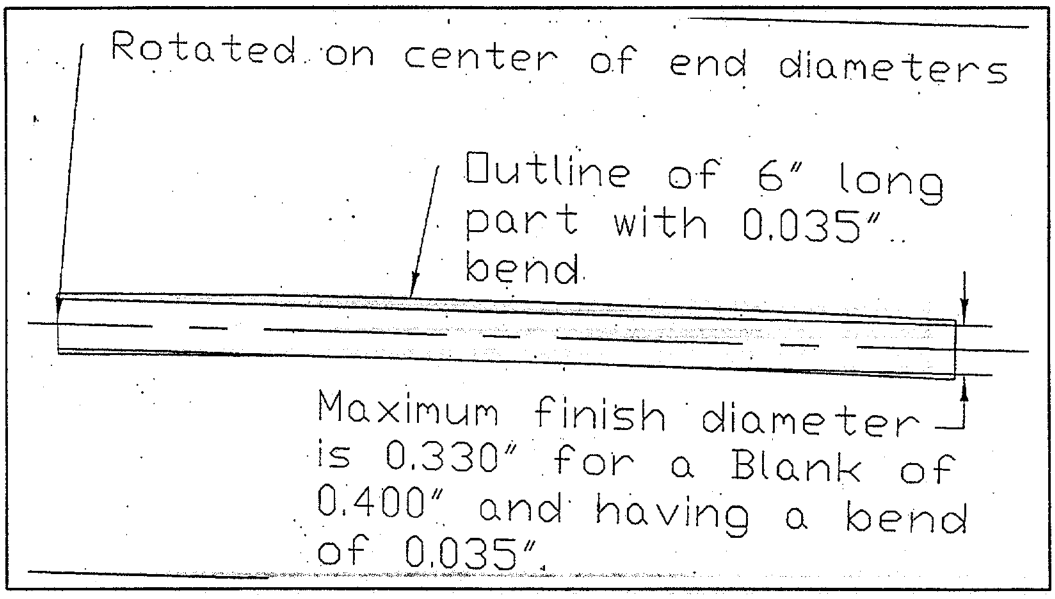


Figure 20. Effect of Valve Stem Bending on Machining (1)

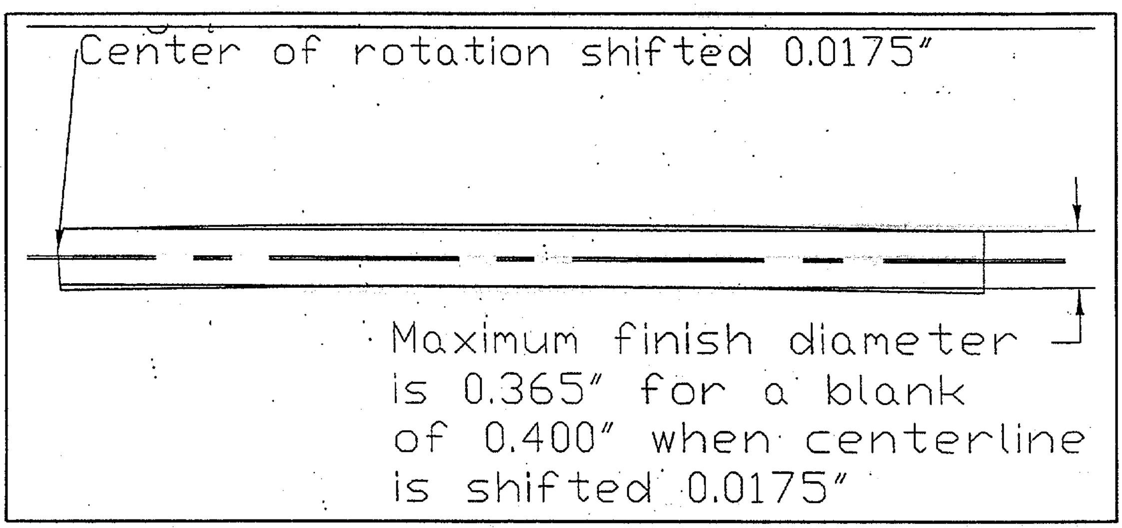


Figure 21. Effect of Valve Stem Bending on Machining (2)

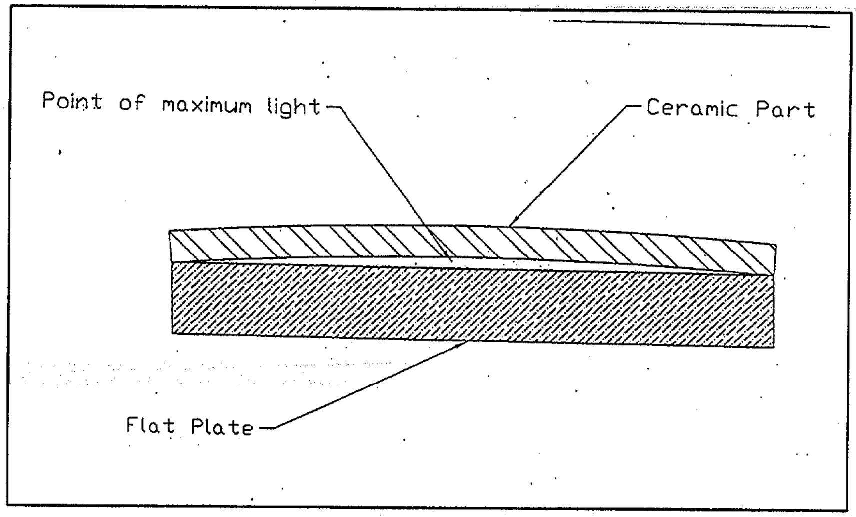


Figure 22. Effect of Valve Stem Bending on Machining (3)

The following grinding wheels were specified for purchase and evaluation on the Studer S40 grinder:

100/120 Grit MSL for Roughing @ 150 m/s
120/140 Grit MSL for Roughing @ 150 m/s
320 Grit Vitrified for Finishing @ 80 m/s
320 Grit Vitrified for Roughing/Finishing @ 80 m/s
20/30 μm Vitrified for Finishing @ 80 m/s
320 Grit Vitrified, Harder Grade and Bond @ 80 m/s
150 Grit Vitrified, Aluminum Core @ 150 m/s
150 Grit Vitrified, Steel Core @ 150 m/s
30/40 μm Vitrified, Steel Core @ 150 m/s

The later work demonstrated that the valve stem, head radius, and seat could be rough ground even without using a steady rest, which resulted in a dramatic reduction in grinding time. A best rough grinding time of only 1.6 min (Setup #2, in Table 16) was ultimately achieved using the setup depicted in Figure 23.

Table 16. Valve CNC Profile Grinding Data (3)

	Current @ NAC	**Vendor A (10/1/95 Report)**	**Vendor A (12/1/95 Report)**	**Vendor A (4/1/96 Setup 1)**	**Vendor A (4/1/96 Setup 2)**
Plunge grind for steady rest	–	–	3.9 min	12 s	–
Rough Stem	10-15 min	6½ min	–	78 s	77 s
Rough Head	7-8 min	3 min	–	66 s	20 s
Total rough grinding time	*17-23 min*	*9.5 min*	*3.4 min*	*2.4 min*	***1.6 min***
Finish Grind	40 min	10 min	10 min	10 min	10 min
Max Total Grinding Time	**57-63 min**	**20 min**	**17.3 min**	**12.6**	**11.6 min**

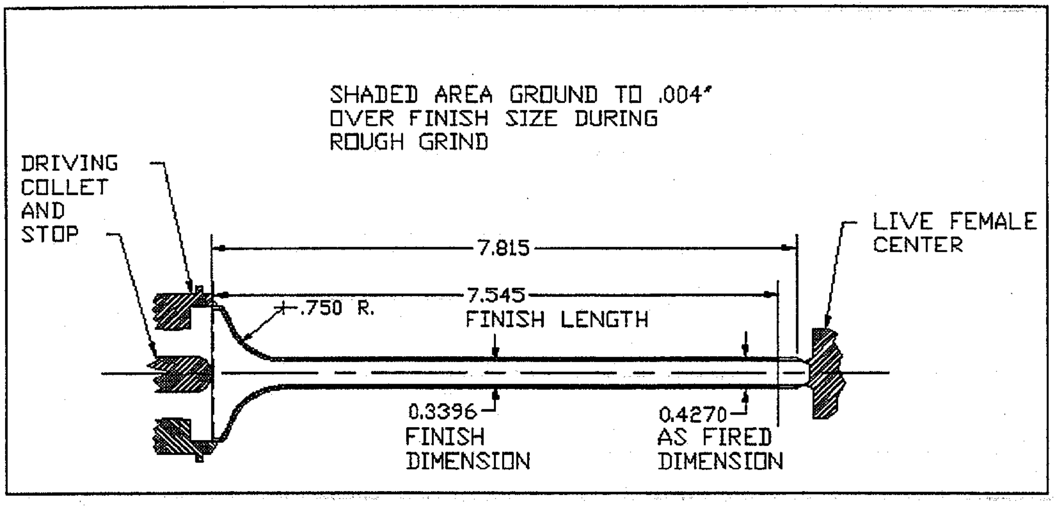


Figure 23. CNC Profile Grinding of Valve on Centers (1)

The time required for finish grinding was the focus of the next series of tests. By plunging the end of the valve stem, grinding the valve stem, grinding the valve seat, and CNC profiling the valve head/radius at operating wheel speed of 80 m/s (Figure 24), the best finishing time was reduced from 10 to 3.78 min.

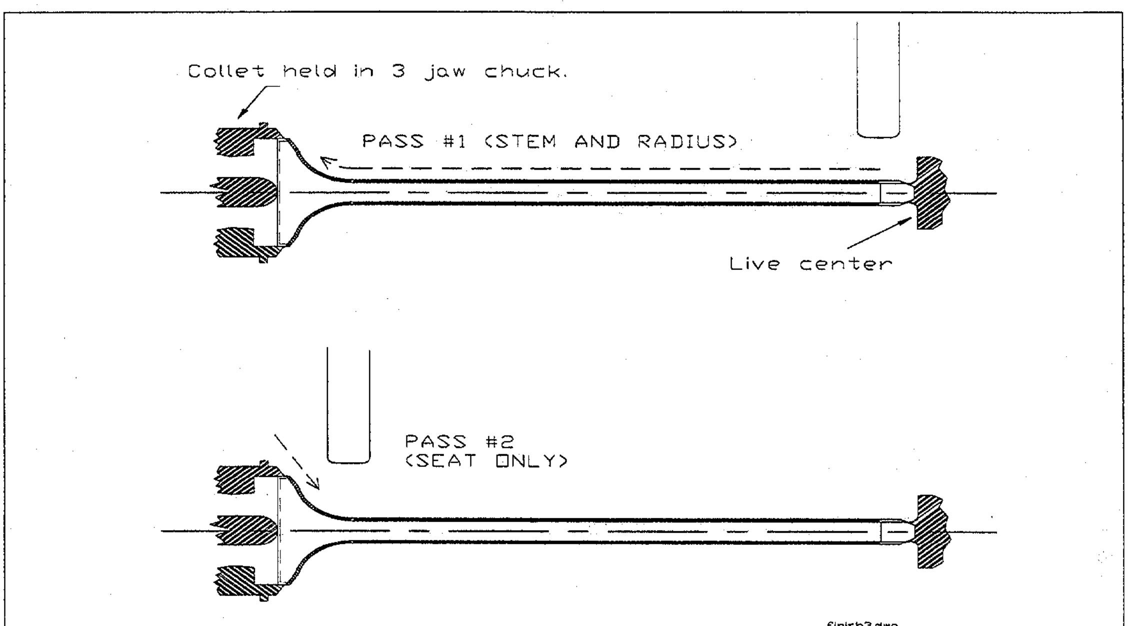


Figure 24. CNC Profile Grinding of Valve on Centers (2)

The best total grinding time was, therefore, reduced from 11.6 to 5.4 min as shown in Table 17.

Table 17. Valve CNC Profile Grinding Data (4)

	Old Process @ NAC	Vendor A (10/1/95 Report)	Vendor A (12/1/95 Report)	Vendor A (4/1/96 Report)	Vendor A (6/1/96 Report)
Plunge grind for steady rest	–	–	3.9 min	–	–
Rough Stem	10-15 min	6½ min	–	77 s	77 s
Rough Head	7-8 min	3 min	–	20 s	20 s
Total rough grinding time	*17-23 min*	*9.5 min*	*3.4 min*	***1.6 min***	***1.6 min***
Finish Grind	40 min	10 min	10 min	10 min	3.8 min
Max total grinding time	**57-63 min**	**20 min**	**17.3 min**	**11.6 min**	**5.4 min**

A chronology of machining improvement in terms of total required time for grinding stem, head radius, and seat is presented in Table 18. Assuming a normalized total machining time of 100% with the base line NAC process, an order of magnitude reduction was realized with the above-described process.

Table 18. Chronology of Machining Improvement

	Baseline Process @ NAC	Vendor A (10/1/95 Report)	Vendor A (12/1/95 Report)	Vendor A (4/1/96 Report)	Vendor A (6/1/96 Report)
Max. Total Grinding Time	**100%**	**33%**	**29%**	**19%**	**9%**

Ultimately, a CNC technique for cost-effectively grinding ceramic valves was successfully established. A significant reduction in machining time was accomplished using a high-speed MSL wheel for roughing and a vitrified diamond wheel for finishing.

CNC Profile Grinding Test, Phase 2. At NAC's request, the following operations for grinding the entire valve, including the keeper groove, the length, and the end chamfer, etc., were successfully developed. It should be noted that the cycle time listed for each operation includes not only the machining time but also the set-up time.

Operation 1 - Grind Valve Head to Fit Collet.

Operation Description. Operation 1 ground the valve-head diameter, allowing it to fit into the collet fixture used in the subsequent operations. Because the head dimension and roundness of the as-fired valve blanks varied, this machining operation was necessary to improve roundness of the head and to permit the valve blank to be held securely in fixturing throughout the machining process. The grinding operation reduced the head diameter from approximately 1.900 in. to 1.862 in., and the roundness from 0.010 in. to 0.0005 in.

Operation Procedure. The Studer S40 CNC machine and the Studer Cycle 9102 Plunge with Oscillation Program were utilized for this operation. The valve blank was held in a rubber-type collet fixture, which was mounted in a three-jaw chuck and corrected for any runout before the fixture was locked into place.

When the fixture was secured, the valve blank was inserted into the collet and the collet was tightened, securing the blank in place (Figure 25). Although the stems of the as-fired valve blanks were out-of-round and varied in diameter, the rubber type collet was flexible enough to compensate for both factors and to firmly hold the valve blanks during grinding.

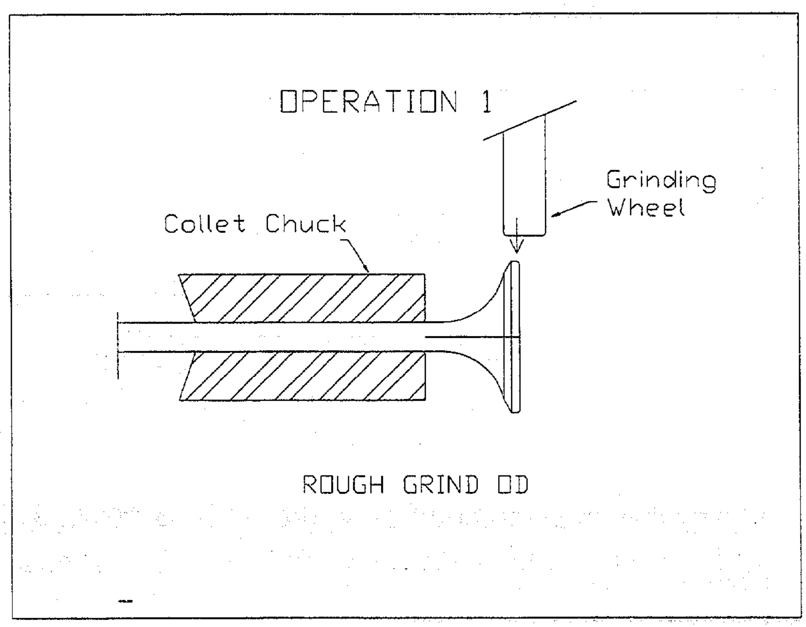


Figure 25. Operation 1: Grind Valve Head to Fit Collet

The head of the valve blank was held approximately 1.250 in. from the collet face. Each valve blank was individually machined to the required dimensions in a plunge/oscillation mode. The machining conditions and grinding wheel information for Operation 1 are shown in Table 19.

Table 19. Machining Parameters for Operation 1

Machine

Machine	Studer S40
Spindle Power	9 kW
Spindle #	1

Grinding Wheel

Wheel Specification	IMG 120/140 H MSL Prod Code 902554M-N
Wheel Shape	1A1
Wheel Dimension	16 in. x 0.515 in. x 5.0 in.

Process Conditions

Wheel Speed	80 m/s, 15,750 SFPM {Wheel Head #1}
Work Speed	500 rpm
Type of Grind Mode	Plunge with Oscillation
Plunge/Oscillation Rate	0.05 in./min/ 10 in./min
Stock Removed	0.040 in. diam
Cycle Time	8 min
Coolant	Crodar Inversol 22
Coolant Concentration	60% Oil 40% Water
Coolant Pressures	Coolant at Grind Zone 725 psi. Two Cleaning Nozzles at 925 psi.
Truing Conditions	No Truing Required to MSL Product

Operation 2 - Cut Off As-Fired End.

Operation Description. The as-fired valve blanks were oversize in length and had a groove from a previous firing process. This section of the valve blank required removal prior to completion of the subsequent operations. Operation 2 reduced the overall length of the valve, and also allowed the grinding of a 30° taper at the end of the valve during Operation 4. The machine used to perform this cutoff operation was a Buehler Isomet 1000 Diamond Saw.

Operation Procedure. The grinding wheel was mounted on the machine spindle and adjusted until runout was less than 0.001 in. The wheel was then conditioned using a dressing stick.

The setup involved clamping the valve-blank stem in the machine fixture and aligning the section to be cut off with the grinding wheel (Figure 26). When the wheel and part had been aligned, the machine was switched to an automatic cycle and the valve cut off. Table 20 shows the machining conditions and parameters used in Operation 2.

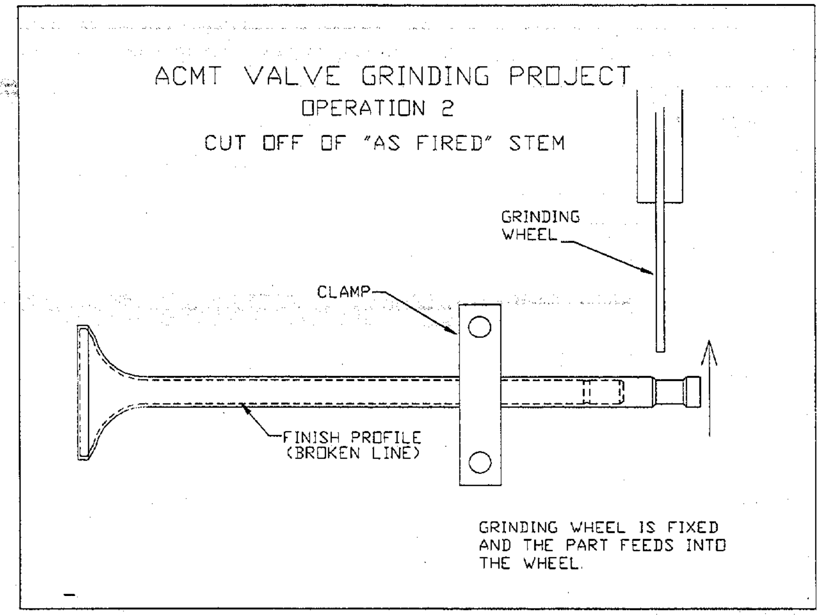


Figure 26. Operation 2: Cut Off As-Fired End

Table 20. Machining Parameters for Operation 2

Machine

Machine	Buehler Isomet 1000 Diamond Saw.
Load Capacity	1000 grams

Grinding Wheel

Wheel Specification	ASD 150 R75BX615C
Wheel Shape	1A1R
Wheel Dimension	6 in. x 3/32 in. x 1/2 in.

Process Conditions

Wheel Speed	2400 rpm
Force Applied	300 g
Type of Grind Mode	Plunge Cutoff
Cycle Time	5 min
Coolant	Master Chemical Trim Clear
Coolant Concentration	5% with DI Water

Truing and Dressing Parameters

Truing Conditions	No Truing Required
Dressing Stick	37C220-KVS
Wheel Speed	2400 rpm
Feed Rate	Manually Fed
Coolant	Using Coolant as Stated Above

Operation 3 - Rough Grind Stem to Reduce Run-out for Operation 4.

Operation Description. Due to straightness, roundness, and dimensional irregularity in the as-fired valve-blank stems, the collet used in Operation 4 would not hold the valve securely or accurately enough. Operation 3 was designed to remove the irregularities in the valve-blank stem prior to Operation 4 by rough grinding along the length of the valve-blank stem.

Operation Procedure. Operation 3 was carried out on the Studer S40 machine using an MSL wheel specification. A single traverse pass ground the valve-blank stem, reducing the stem diameter by approximately 0.02 in. to 0.400 in. (Figure 27).

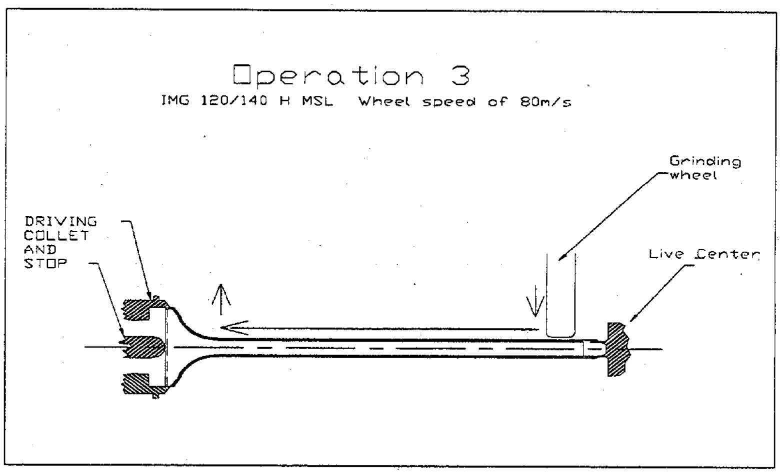


Figure 27. Operation 3: Rough Grind Stem to Reduce Run-out for Operation 4

During this operation the valve was held in place with the same method used to finish the valves; the valve head was secured in a collet and the end supported in a 60° live female center.

Table 21 details the machining conditions and parameters utilized in Operation 3.

Table 21. Machining Parameters for Operation 3

Machine

Machine	Studer S40
Spindle Power	9 kW
Spindle #	1

Grinding Wheel

Wheel Specification	IMG 120/140 H MSL Prod Code 902554M-N
Wheel Shape	1A1
Wheel Dimension	16 in. x 0.515 in. x 5.0 in.

Process Conditions

Wheel Speed	80 m/s, 15,750 SFPM {Wheel Head #1}
Work Speed	1000 rpm
Type of Grind Mode	Traverse
Traverse Rate	7 in./min
Traverse Length	6.00 in.
Stock Removed	0.020 in. diam
# of Passes	1
Cycle Time	4 min
Coolant	Crodar Inversol 22
Coolant Concentration	60% Oil 40% Water
Coolant Pressures	Coolant at Grind Zone 725 psi. Two Cleaning Nozzles at 925 psi.
Truing Conditions	No Truing Required to MSL Product

Operation 4 - Grind 60° Angle on Stem to Fit Live Female Center.

Operation Description. This operation machined the angle on the end of the valve blank in order to fit the valve end in a 60° live female center fixture. It was found during previous testing that the as-fired 60° angle on the blank was causing roundness problems on the finish valve-blank stems. This was caused by the angle not being geometrically accurate enough to fit tightly into the female center, and by consequent movement of the valve blank during the finishing operations. It was, therefore, determined that the 60° angle must be ground prior to the finishing operations. In order to grind this angle, the valve blank was held by its stem in a collet.

Operation Procedure. This was a manual plunge grind operation. The valve was mounted in a collet, and runout of the stem was reduced to less than 0.005 in. The operation was completed on a Brown & Sharpe Universal grinder. Due to limitations of the machine, and in order to achieve the 60° included angle, both the workhead and the wheelhead had to be angled (Figure 28). The wheel was manually plunged straight into the valve, forming the angle. The machining conditions and parameters used in Operation 4 are shown in Table 22.

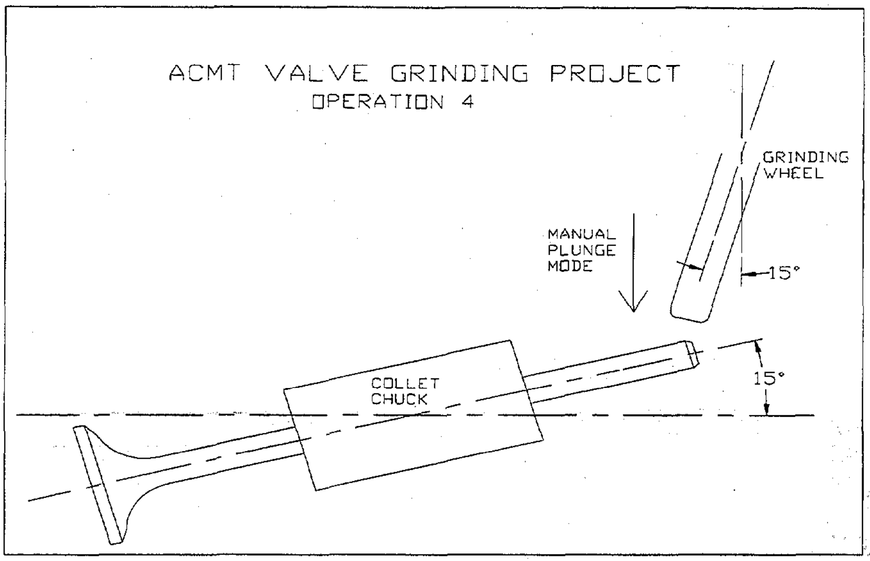


Figure 28. Operation 4: Grind 60° Angle on Stem to Fit Live Female Center

Table 22. Machining Parameters for Operation 4

Machine

Machine Used	Brown & Sharpe 10 in. Universal
Maximum Spindle Power Available	1.5 hp

Grinding wheel

Wheel Shape	1A1
Wheel Specification	SD400-R100B56 1/16 in.
Wheel Dimensions	9 in. x 0.250 in. x 3 in.

Process Condition

Wheel Speed	5500 SFPM
Work Speed	150 rpm
Type of Grind Mode	Manual plunge
Cycle Time	10 min
Coolant Used	Master Chemical Trim Clear
Coolant Concentration	5% with DI Water

Wheel Conditioning Procedure

Dressing Stick	37C220HVS
Dressing Method	Manually Fed into Wheel

Operation 5 - Rough Grind Stem, Radius, and Seat

Operation Description. Operation 5 rough ground the stem, the seat, and the 0.75 in. radius. This operation was a single pass, profile traverse grind, carried out on the Studer S40 grinding machine.

Fixturing the valve involved securing the valve head, at the workhead side of the machine, in a collet. The collet was held in a four-jaw chuck, which allowed the valve to be adjusted for minimal runout. The other end of the valve was supported by the tailstock, using a live female center (Figure 29).

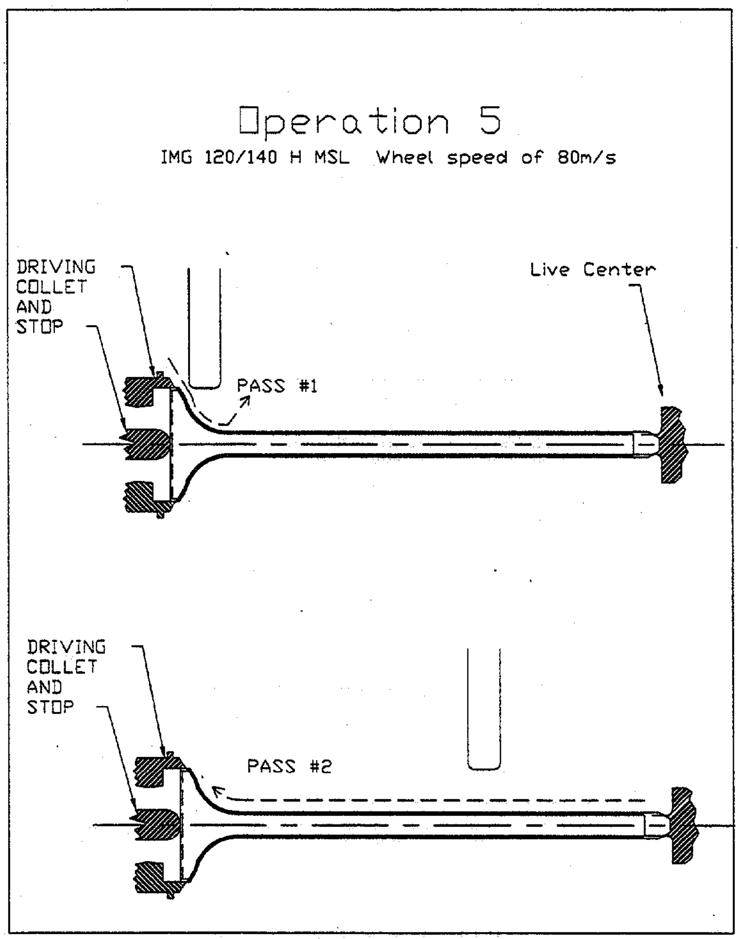


Figure 29. Operation 5: Rough Grind Stem, Radius, and Seat

The grinding wheel used was an MSL wheel with a 0.100 in. radius on each corner.

Operation Procedure. The valve was placed in the fixture and secured. The machine was put into an automatic mode, and the valve was profile ground. Due to the fact that the valve was removed from the machine after roughing and placed back in the machine for the finishing operation, it was necessary to leave 0.007 in. - 0.008 in. stock for finishing. This ensured that the valve would clean completely during the finishing operation.

The machining conditions and parameters used in Operation 5 are provided in Table 23.

Table 23. Machining Parameters for Operation 5

Machine

Machine	Studer S40
Spindle Power	9 kW
Spindle #	1

Grinding Wheel

Wheel Specification	IMG 120/140 H MSL Prod Code 902554M-N
Wheel Shape	1A1 (0.100 radii)
Wheel Dimension	16 in. x 0.515 in. x 5.0 in.

Process Conditions

Wheel Speed	80 m/s, 15,750 SFPM {Wheel Head #1}
Work Speed	1000 rpm
Type of Grind Mode	Profile Traverse
Traverse Rate: Stem Radius Seat	 3.5 in./min 0.75 in./min 1.5 in./min
Stock Removed	0.055 in. diam
Final Part Dimensions (Stem)	0.3456 diam
# of Passes	1
Surface Finish Requirements	N/A
Cycle Time	4 min
Coolant	Crodar Inversol 22
Coolant Concentration	60% Oil 40% Water
Coolant Pressures	Coolant at Grind Zone 725 psi. 2 Cleaning Nozzles at 925 psi
Truing Conditions	No Truing Required to MSL Product

Operation 6 - Finish Grind Stem, Radius, and Seat

Operation Description. Operations 6 and 7 were completed in one setup. Each valve was finish machined on the stem, radius, and seat (Operation 6); then the keeper groove was machined (Operation 7) without removing the valve. Previous testing had demonstrated that the keeper groove was one of the primary areas of failure during pull testing. Therefore, the machining procedure was designed so that the stem and seat would be machined in the same setup as the keeper groove, thereby minimizing runout between these key locations. Another advantage of machining the seat and keeper groove in the same setup is the ease with which the seat-to-the-keeper-groove location can be maintained within tolerance. Otherwise, this would be a difficult location tolerance to maintain without special tooling.

Due to differences between the quality and geometric requirements of the two operations, two grinding wheels were needed to complete this process. One wheel ground the stem, seat, and radius; the other ground the keeper groove. Therefore, these two operations utilized both spindles on the Studer grinder.

Operation Procedure. In order to hold dimensional tolerances, two finishing passes were necessary. A total of 0.007 in.- 0.008 in. remained on the diameter after roughing.

As in the roughing operation, the valve was held in a collet and a female live center (Figure 30).

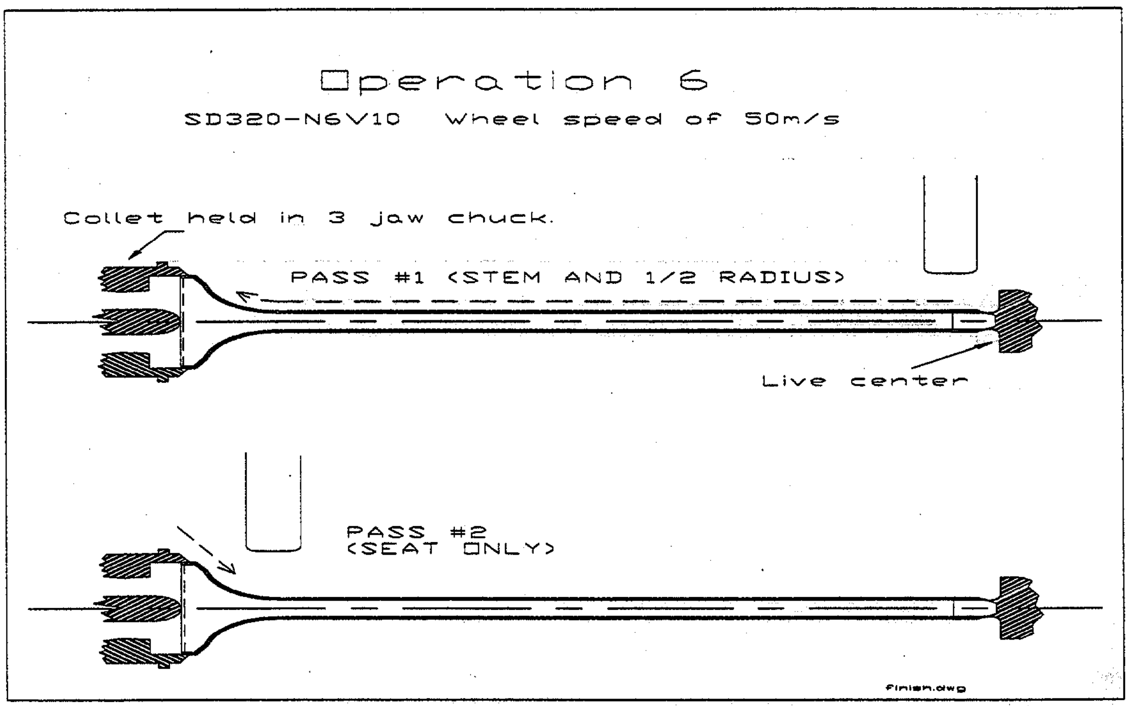


Figure 30. Operation 6: Finish Grind Stem, Radius, and Seat

To achieve the required surface finish on the seat, an angled flat section on the corner radius of the wheel face was required. Forming this geometry was accomplished by utilizing the profile dress option of the Studer machine. The angle of the flat on the grinding wheel matched the valve seat, allowing the 60° +/-15° angle to be machined in a traverse mode (Figure 31).

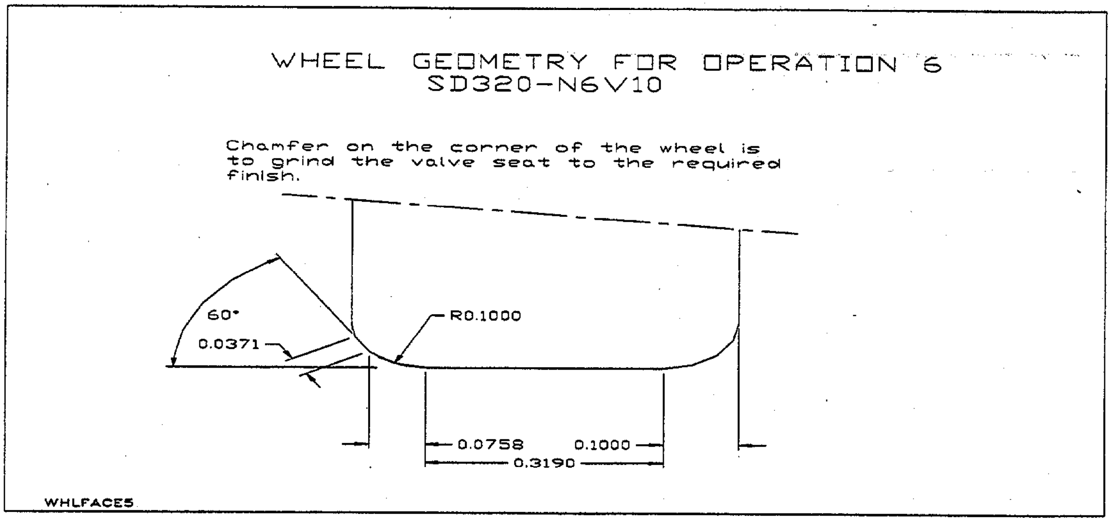


Figure 31. Operation 6: Wheel Geometry

Wheel Conditioning. In order to reduce runout and meet geometric requirements, the grinding wheel required truing. Runout of the wheel periphery was checked using a 0.00005-in. dial indicator and was kept within 0.0001-in. TIR. The wheel shape was designed based on results from previous tests. Testing showed that, in order to achieve a good finish on the seat, a flat-angle section was required on the side of the wheel. Also, in order to achieve the necessary finish on the 0.75-in. radius, the wheel required a 0.050-in. radius (Figure 31). During the grinding operation the wheel needed truing every 5 parts. Figure 32 shows the setup of the truing unit in relation to the grinding wheel.

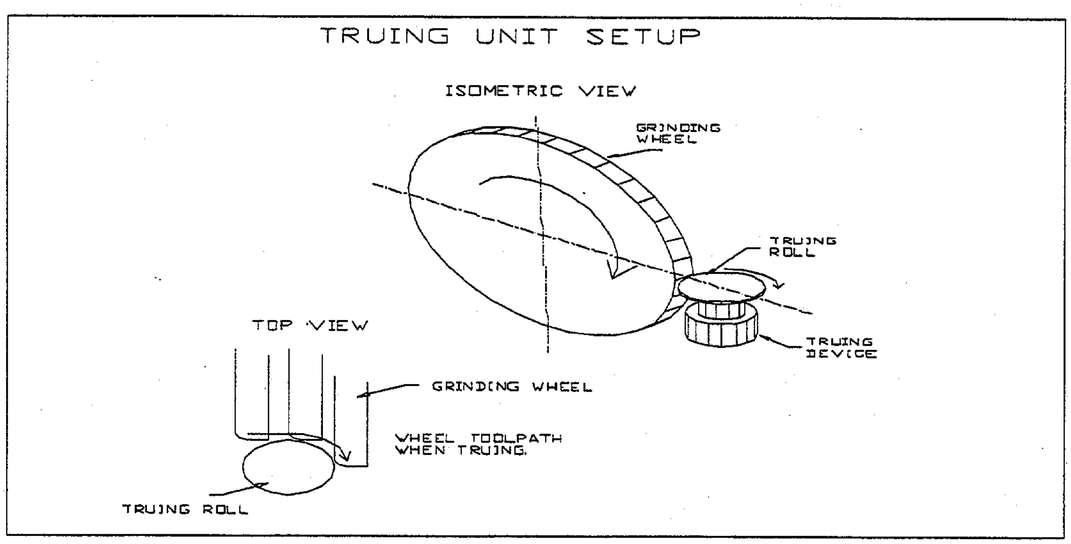


Figure 32. Operation 6: Truing Unit Setup

As shown in Figure 32, the truing wheel was mounted perpendicular to the grinding wheel. This method of truing the wheel ensured that the radius formed on the wheel was a true radius. Conventional methods use a truing roll with a pre-formed corner radius running parallel to the wheel. This radius wears over time and results in the formation of a non-uniform radius on the grinding wheel. The perpendicular method allows the roll to wear evenly on the radius. This ensures that the radius on the wheel is always a true radius. In order to maintain the correct size of radius on the wheel, the change in the roll size is compensated for in the machine control (cutter compensation).

Table 24 shows the machining conditions and parameters of Operation 6.

Table 24. Machining Parameters for Operation 6

Machine

Machine	Studer S40
Spindle Power	9 kW
Spindle #	2

Grinding Wheel

Wheel Dimension	16 in. x 0.515 in. x 5.0 in.
Wheel Shape	1A1 (See Figure 31 on Page 60)
Wheel Specification	SD320-N6V10

Process Conditions

Wheel Speed	50 m/s, 9850 SFPM, {Wheel Head #2}
Work Speed	1000 rpm
Type of Grind Mode	Profile Traverse
Traverse Rate Stem	8 in./min
Traverse Rate Radius	0.3 in./min / 0.5 in./min
Traverse Rate Seat	0.6 in./min
Stock Removed	0.007 in. diam
Final Part Dimensions (Stem)	0.3396 in. diam
# of Passes	2-3 Passes as Necessary
Cycle Time	9 min
Coolant Used	Crodar Inversol 22
Coolant Concentration	60% Oil 40% Water
Coolant Pressures	Coolant is Delivered to the Grind Zone at 72.5 psi.

Critical Tolerances

Stem Diameter	0.3396 in. ±0.0004 in.
Stem, Radius & Seat Surface Finish	8 Ra μ in.
Stem Straightness	.0004 in.
Seat Angle	30° +/-15°
Runout Seat To Stem	.002 in.

Truing Equipment

Truing Device	Norton Hydraulic Device Model # AXH1416
Diamond Roll	Wendt 2351.098 575C008006 CARAB 005
Roll/Wheel Setup	Roll Perpendicular to Wheel

Truing Conditions

Dress Compensation	0.00002 in.
Dress Cross-Feed on Wheel Face	10 in./min
Dress Crossfeed on Wheel Face Radius and Chamfer	5 in./min
Truing Wheel Speed	3000 rpm
Grinding Wheel Speed	2000 SFPM.
Coolant Application	Same as Grinding Conditions.
Truing Frequency	Every 5 Parts

Operation 7 - Grind Keeper Groove

Operation Description. As mentioned in the description of Operation 6, each valve was finish machined on the stem, radius, and seat (Operation 6); then the keeper groove was machined in the same setup (Operation 7). This operation used a resinoid bonded wheel mounted on wheel head #1.

Operation Procedure. The keeper groove was ground in a plunge mode (Figure 33). The distance from the seat reference position to the keeper groove was located by grinding a setup piece. The valve was then inspected, and the keeper-groove location adjusted for any error. When the correct position was found, the position was fixed into the CNC cycle and required only minor adjustments to compensate for wheel wear throughout the run.

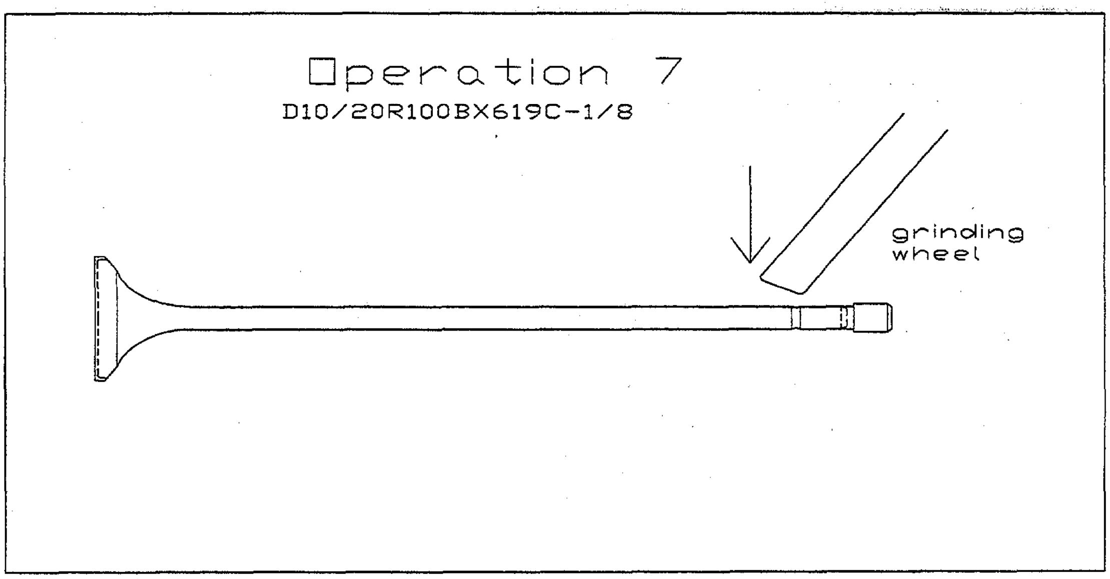


Figure 33. Operation 7: Grind Keeper Groove

Wheel Conditioning. The grinding wheel required the form of the keeper groove to be trued into the wheel. Prior to grinding the keeper groove, the wheel was trued with a 0.053-in. radius on the working corner. This radius matched the required keeper-groove radius. The wheel was then swiveled to a 30° angle in order to create the keeper-groove shape.

The machining conditions and parameters used in Operation 7 are shown in Table 25.

Table 25. Machining Parameters for Operation 7

Machine

Machine	Studer S40
Spindle Power	9 kW
Spindle #	1

Grinding Wheel

Wheel Dimension	16 in. x 0.500 in. x 5.0 in.
Wheel Shape	1A1 with 0.056 radius on Each Edge
Wheel Specification	D10/20R100BX619C-1/8 (Item #0732728)

Process Conditions

Wheel Speed	80 m/s, 15750 SFPM, {Wheel Head #1}
Work Speed	rpm
Type of Grind Mode	Plunge
Plunge Rate	0.05 in./min
Final Part Dimensions (Stem)	0.2965 in. diam
Cycle Time	1 min 30 s
Coolant Used	Crodar Inversol 22
Coolant Concentration	60% Oil 40% Water
Coolant Pressures	725 psi. at Grind Zone. 925 psi. for Two Cleaning Nozzles

Critical Tolerances

Runout to Stem	0.003 in.
Angle	30° +/-15'
Radius	0.050/0.056
Distance from Seat Reference	6.886/6.901
Diameter	.293/.300
Surface Finish	8 µin. Ra

Truing Equipment

Truing Device	Norton Hydraulic Device Model # AXH1416
Diamond Roll	Wendt 2351.098 575C008006 CARAB 005
Roll/Wheel Setup	Roll Perpendicular to Wheel (See Figure 32 on Page 60)

Truing Conditions

Dress Compensation	0.00002 in.
Dress Crossfeed on Wheel Face	10 in./min
Dress Crossfeed on Radius	5 in./min
Truing Wheel Speed	3000 rpm
Grinding Wheel Speed	2000 SFPM.
Coolant Application	Same as Grinding Operation
Truing Frequency	Every 5 Parts

Operation 8 - Cut-off of Valve Stem

Operation Description. Operation 8 involved cutting the valve stem to length, leaving 0.010-in. stock for finishing.

Operation Procedure. The grinding wheel was mounted on the machine spindle and adjusted until runout was less than 0.001 in. The wheel was then conditioned using a dressing stick.

The setup involved clamping the valve stem in the machine fixture and aligning the section to be cut off with the grinding wheel (Figure 34). When the wheel and part had been aligned, the machine was switched to an automatic cycle, and the valve was cut off.

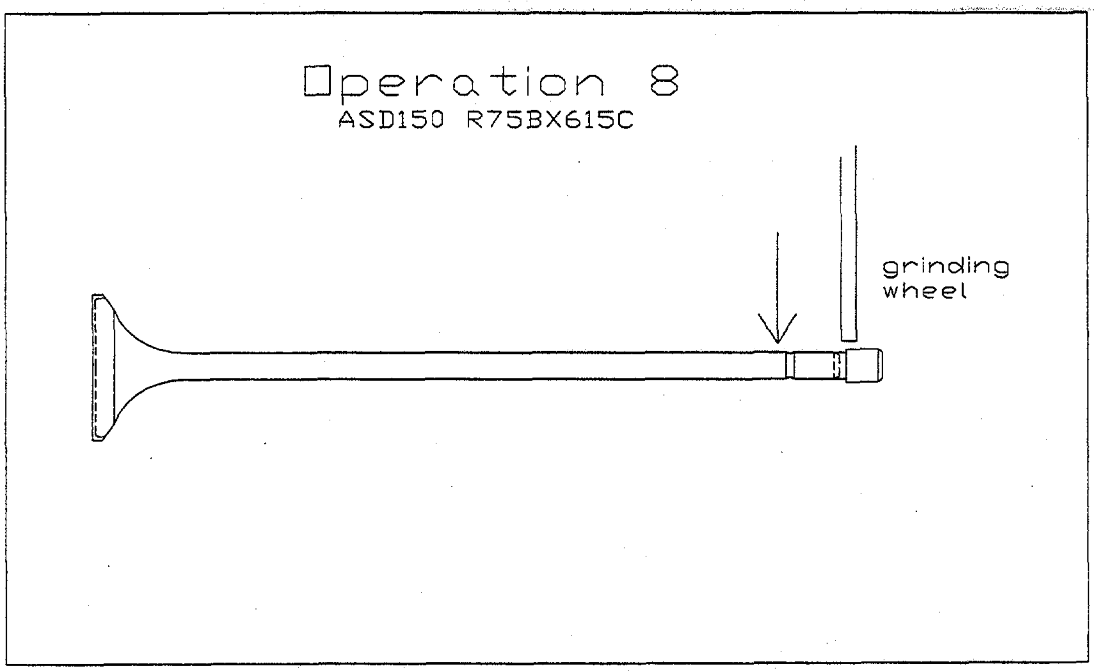


Figure 34. Operation 8: Cut-off of Valve Stem

Table 26 provides the machining conditions and parameters used in Operation 8.

Table 26. Machining Parameters for Operation 8

Machine

Machine	Buehler Isomet 1000 Diamond Saw.
Load Capacity	1000 grams

Grinding Wheel

Wheel Specification	ASD 150 R75BX615C
Wheel Shape	1A1R
Wheel Dimension	6 in. x 3/32 in. x 1/2 in.

Process Conditions

Wheel Speed	2400 rpm
Force Applied	300 g
Type of Grind Mode	Plunge Cutoff
Coolant	Master Chemical Trim Clear
Coolant Concentration	5% with DI Water

Truing and Dressing Parameters

Truing Conditions	No Truing Required
Dressing Stick	37C220-KVS
Wheel Speed	2400 rpm
Feed Rate	Manually Fed
Cycle Time	5 min
Coolant	Using Coolant as Stated Above

Operation 9 - Finish Grind of Valve Head Face and Valve Head Diameter.

Operation Description. Operation 9 finish ground the head diameter, the 0.040/0.025-in. radius and the face to finish dimension.

Operation Procedure. The valve was held by the stem in a collet chuck. An extension support fixture was added to one end of the collet to give support to the valve head. This assembly was mounted in an 8 in., three-jaw chuck and, using a reference surface on the collet, the chuck was indicated to within 0.0005 in. TIR.

Using an MSL wheel that was tilted at a 10° angle to allow side clearance, the face of the valve was ground. The wheel head was then returned to 0°, and the valve-head diameter was machined to size in a plunge/oscillation mode. After 3 spark out passes, the wheel continued to grind the 0.040/0.025-in. radius at the intersection of the head diameter and face (Figure 35).

Table 27 shows the machining conditions and parameters utilized for Operation 9.

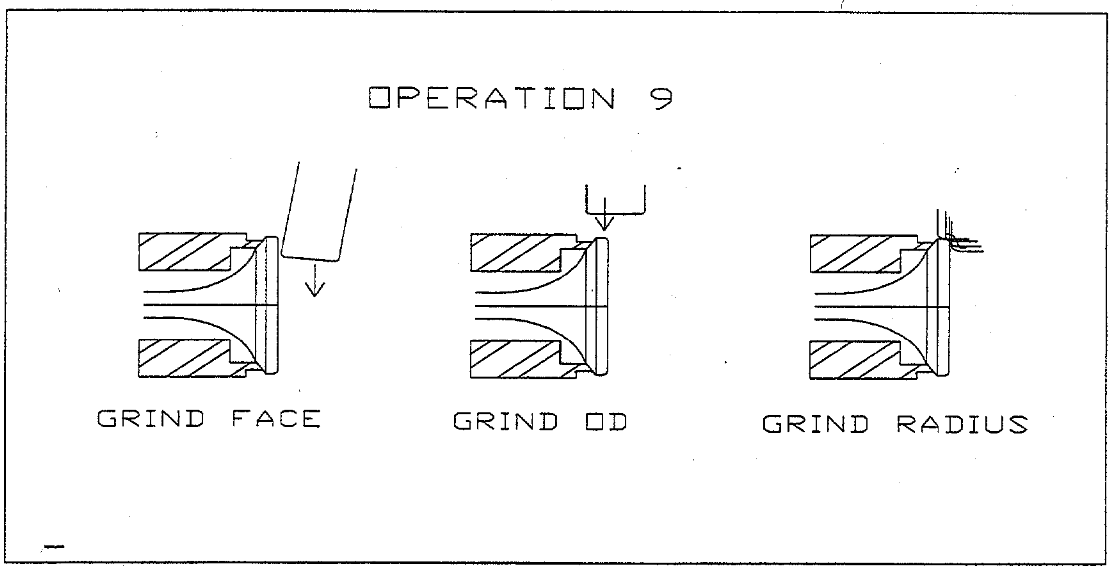


Figure 35. Operation 9: Finish Grind of Valve Head Face and Diameter

Table 27. Machining Parameters for Operation 9

Machine

Machine	Studer S40
Spindle Power	9 kW
Spindle #	1

Grinding Wheel

Wheel Specification	IMG 120/140 H MSL Prod Code 902554M-N
Wheel Shape	1A1
Wheel Dimension	16 in. x 0.515 in. x 5.0 in.

Process Conditions

Wheel Speed	80 m/s, 15,750 SFPM {Wheel Head #1}
Work Speed	800 rpm
Type of Grind Mode	Plunge/Oscillation Profile
Plunge Rate on Face	0.32 in./min
Plunge Rate on Head	0.40 in./min
Traverse Rate on Radius	0.25 in./min
Stock Removed for Face	Approx. 0.050 in. to 0.080 in.
Stock Removed for Head Diameter	0.060 in. diam
Cycle Time	8 min
Coolant	Crodar Inversol 22
Coolant Concentration	60% Oil 40% Water
Coolant Pressures	Coolant at Grind Zone 725 psi; 2 Cleaning Nozzles at 925 psi
Truing Conditions	No Truing Required to MSL Product

Critical Tolerance

Head Diameter	1.798 in. ± 0.005 in.
Corner Radius	0.040/0.025
Datum to Face	0.1425 in. ± 0.0009 in.
Surface Finish	16 µin Ra

Operation 10 - Grind Valve Length and End Chamfer.

Operation Description. Operation 10 ground the valve stem to length and finish machined the 60° angle (Figure 36).

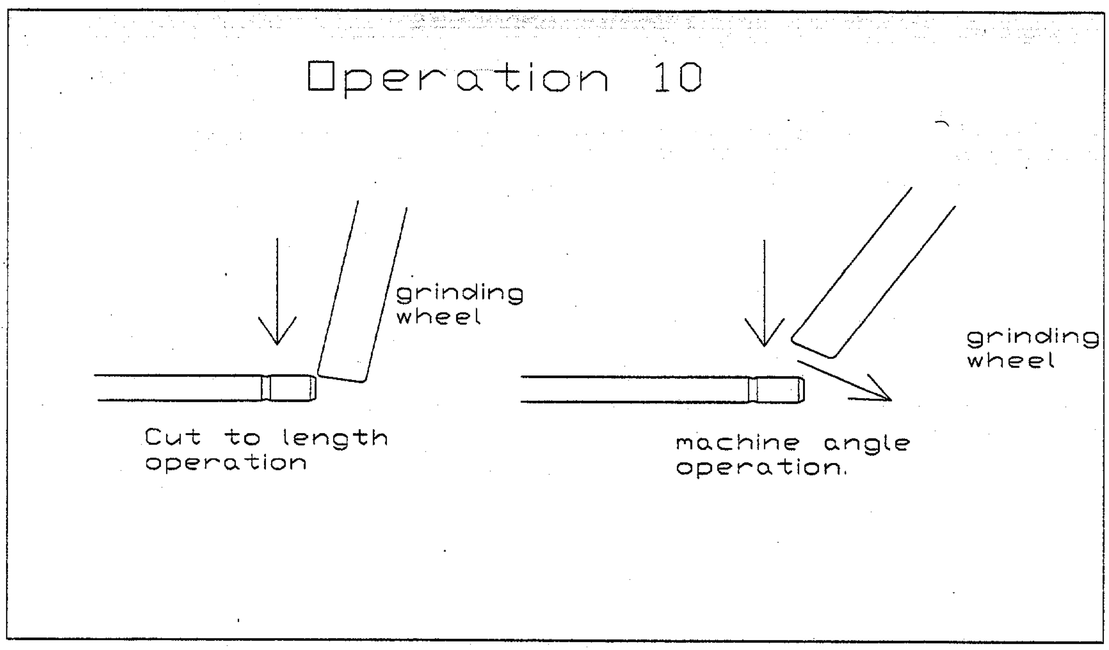


Figure 36. Operation 10: Grind Valve Length and End Chamfer

Operation Procedure. The valve was mounted in the same collet fixture used for Operation 9. The wheel was angled 10° and a plunge mode was used to grind the stem to length. The chamfer was ground by angling the wheel to 30° and traverse grinding across the face. Using a traverse grind and angling the wheel helped to achieve the required surface finish.

The machining conditions and parameters used in Operation 10 are shown Table 28.

Table 28. Machining Parameters for Operation 10

Machine

Machine	Studer S40
Spindle Power	9 kW
Spindle #	1

Grinding Wheel

Wheel Specification	IMG 120/140 H MSL Prod Code 902554M-N
Wheel Shape	1A1
Wheel Dimension	16 in. x 0.515 in. x 5.0 in.

Process Conditions

Wheel Speed	80 m/s, 15,750 SFPM {Wheel Head #1}
Work Speed	500 rpm
Type of Grind Mode	Plunge -- Traverse
Traverse Rate on Angle	1.0 in./min
Plunge Rate on End	0.3 in./min
Stock Removed for End	0.020 in. - 0.090 in.
Cycle Time	3 min 30 s
Coolant	Crodar Inversol 22
Coolant Concentration	60% Oil 40% Water
Coolant Pressures	Coolant at Grind Zone 725 psi. Two Cleaning Nozzles at 925 psi.
Truing Conditions	No Truing Required to MSL Product

Critical Tolerances

Valve Length	7.400 in. ±0.005 in.
Chamfer Angle	60° +/-2°
Chamfer Diameter	0.280 in. ±0.005 in.
Surface Finish	16 µin Ra

Operation 11 - Breaking Sharp Edge on Keeper Groove Corner and Seat/ Radius Intersection.

Operation Description. Operation 11 removed the sharp corners on the keeper groove and the seat radius intersection.

Operation Procedure. Any machine with an 8-in. chuck or larger could be used to carry out this operation. The valve was mounted in the same collet fixture used for Operations 8 and 9 and was placed into the machine chuck. The sharp edge was removed manually using a diamond honing stick while the part rotated at 400 rpm. The corner break was inspected on a comparator.

Table 29 details the Operation 11 machining conditions and parameters.

Table 29. Machining Parameters for Operation 11

Machine	Internal Grinder with 8 in. Chuck
Honing Stick	ASD 400-R100 B99
Work Speed	400 rpm
Cycle Time	8 min

The best grinding time achieved in Phase 2, compared with all the previous results, is shown in Table 30.

Table 30. Phase 2 Grinding Time Comparison

	Old Process @ NAC	**Vendor A (10/1/95 Report)**	**Vendor A (12/1/95 Report)**	**Vendor A (4/1/96 Report)**	**Vendor A (6/1/96 Report)**	**Vendor A (Thirty Entire Valves)**
Plunge Grind for Steady Rest	–	–	3.9 min	–	–	
Rough Stem	10-15 min	6½ min	–	77 s	77 s	2 min*
Rough Head	7-8 min	3 min	–	20 s	20 s	2 min**
Total Rough Grinding Time	*17-23 min*	*9.5 min*	*3.4 min*	***1.6 min***	***1.6 min***	
Finish Grind	40 min	10 min	10 min	10 min	3.8 min	7 min***
Max. Total Grinding Time	**57-63 min**	**20 min**	**17.3 min**	**11.6 min**	**5.4 min**	**11 min**

* Operation 3 Machining Time - Rough Grind Stem.
** Operation 5 Machining Time - Rough Grind Stem, Radius, and Seat.
*** Operation 6 Machining Time - Finish Grind Stem, Radius, and Seat with 2 Passes vs 1.

Following the procedures described above, an additional thirty valves were completely machined (rough and finish ground) at Vendor A's facility. All thirty valves met the customer requirements for both stem diameter (±0.0004 in.) and surface finish (<8 µin.). The valves were subsequently measured by NRDC and proof tested in accordance with DDC's specifications.

Proof Test Results.

Dimensional Measurement Results. All key dimensional features of the Series 149 valves machined by Vendor A were inspected at the NRDC machining laboratory using state-of-the-art measurement devices such as the Rank profilometer and Federal roundness equipment. Key valve dimensions measured included stem diameter and roundness, lock groove diameter and taper, and seat angle. The measured dimensions were compared with the valve print to establish the accuracy of the machining procedures. Based upon this detailed inspection, Vendor A demonstrated superior dimensional accuracy (Appendix B).

Pull Test Results. Valve pull tests were performed using a specially designed fixture on the Instron Machine and the appropriate keepers (material and design) received from DDC. All the valves were proof tested up to a predetermined applied pull load as per DDC's specifications. Subsequently, 10 valves were tested to failure. Failure load and its location on the valve were documented for each valve. Once again, Vendor A valves were found to be superior. An additional 150 valves were completely finish machined by Vendor A and were delivered to DDC for durability testing.

Compound Centerless Grinding (Vendor C). The Compound Centerless Grinding approach is similar to Plunge Centerless Grinding (PCG) in terms of machining efficiency and cost effectiveness. In fact, the cost analysis performed by IBIS Associates on PCG at high-volume production quantities varies only 5% from price quotes received from Vendor C.

The main differences between the two approaches are as follows. Contrary to PCG, Compound Centerless Grinding does not require form grinding wheels and, hence, is not sensitive to wheel wear. In addition, the grinding marks on valves machined using the Compound Centerless technique are parallel to the stem axis and, therefore, are relatively benign. Conversely, use of the PCG grinding method results in transverse grinding marks on the valve stem and, consequently, in lower pull strength.

Vendor C was engaged late in the course of the program and, therefore, was primarily involved in the machining of the production demonstration valves. A set of these valves was eventually tested by DDC in the Series 149 engine, as described in Section 7.3.2.

Peel Grinding (Vendor D). The Peel Grinding machining technology has been pioneered by Junker Machinen, Nordrach, Germany, and effectively applied to fabricate silicon nitride valves. Therefore, NAC worked with Vendor D to complete a ceramic valve grinding demonstration at Junker Machinen, Nordrach, Germany. The purpose of these trials was to evaluate the Junker Quickpoint high-speed grinding technology with respect to grinding cycle time, dimensional control process capability, and surface finish. A total of 35 Series 149 NT451 SiAlON valve blanks were ground on a Junker Quickpoint Model 5004 machine tool. A schematic of the grinding process used for these trials is shown in Figure 37. On a separate machine tool, the blanks were first placed in a fixture locating on their stem O.D. Chamfers were ground on each end to hold the part in the Model 5004 during the profile grinding operation. Profile grinding consisted of: (1) a single, rough-profile pass with a diamond metal bond wheel (left side) that traversed the seat, underhead radius, and stem; and (2) a single, finish-profile pass with a diamond metal bond wheel (right side) that traversed only the straight portion of the stem. A total of 15 valves were profile ground to final tolerance and finish using fixed grinding parameters. These valves were returned to NAC for detailed characterization of their dimensions and surface finish. All of the profiled valve blanks met the surface finish and dimensional specifications.

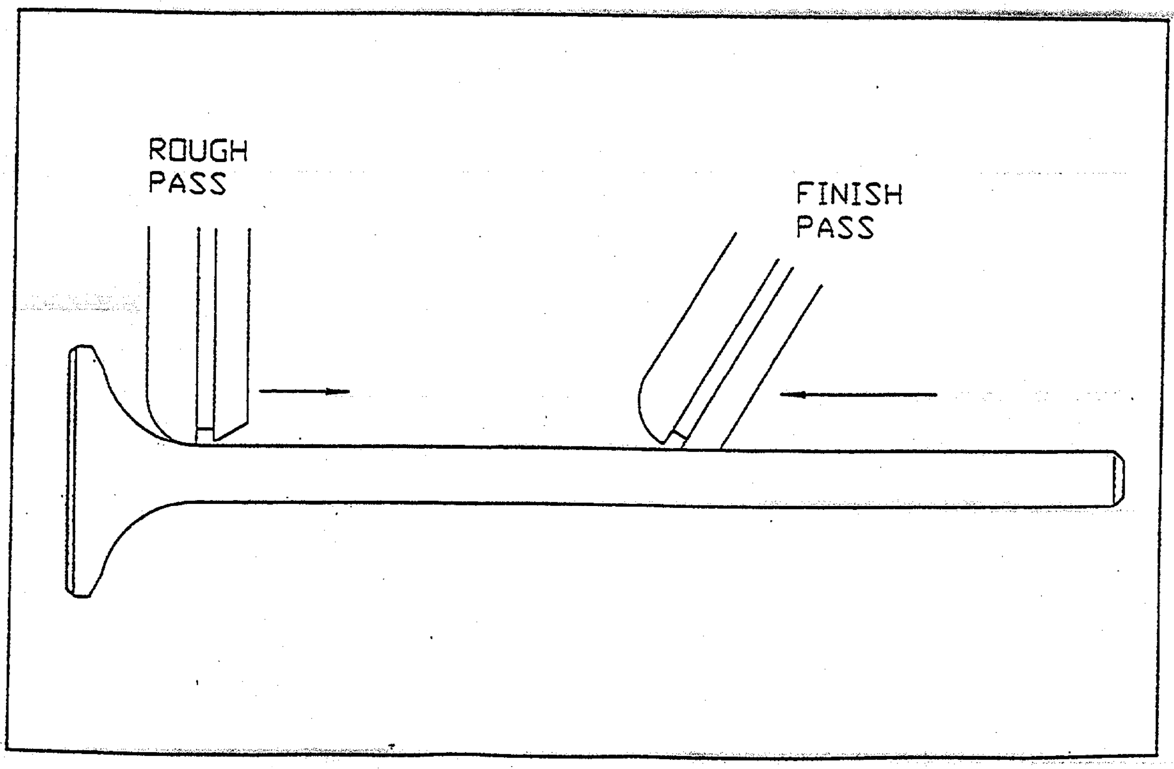


Figure 37. Schematic of Junker Profile Process

A comparison of stem diameter dimensional control down the length of the valve for the Junker process versus NAC's baseline process is shown in Figure 38. Although there is no apparent difference in the profile of stem-diameter down the length of the valve, the Junker process exhibits less process variability. A comparison of stem-diameter process capability for the two profile grinding processes, shown in Figure 39, indicates that the Junker process has superior process potential (C_p). In addition, the Junker process reduced the profile grinding cycle time by a factor of 16 over NAC's baseline process.

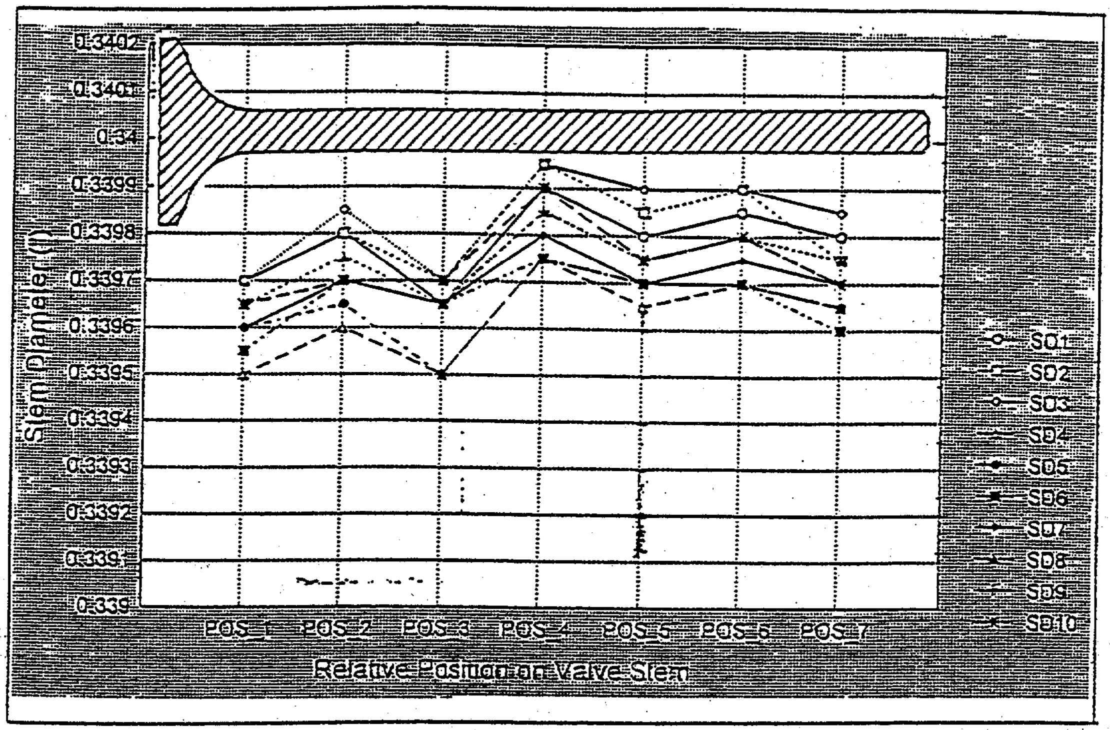


Figure 38. Stem Diameter as a Function of Location on the Stem

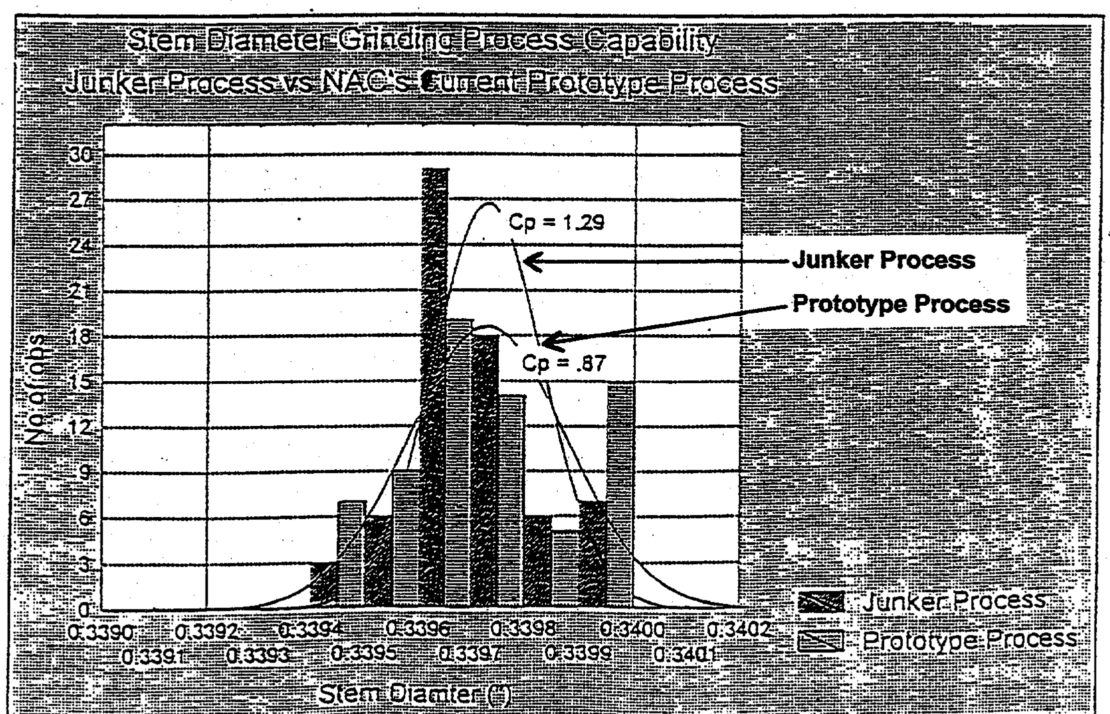


Figure 39. Summary of Stem Diameter Process Capability

The Peel Grinding technology for fabricating silicon nitride valves has been established by Junker Machinery and successfully demonstrated to fabricate finished valves of small size for gasoline engines and to a greater extent, larger diesel engine valves of the current program. The existing machining set-up for smaller valves was modified in order to accommodate the larger diesel valves of the current program. These modifications were less than adequate, which resulted in some deviations in the dimensional tolerances. However, the peel ground valves met all pull strength requirements established by DDC. The cost estimate of this technique is also comparable to other machining procedures (Vendor A, B, and C). Thus, with the proper machining set up, Peel Grinding is expected to be a competitive technique for the fabrication of silicon nitride valves.

7.2.4 Intelligent Process Control - Task 2d

NAC worked together with its R&D group, located at SGIC's Northboro, MA, Research and Development Center (NRDC) and BDM Federal, Inc./MATSYS, Inc. to develop intelligent-processing methodologies for ceramic valve manufacturing. The objectives of this effort were to: (1) develop, implement, and demonstrate an intelligent control system (ICS) for the milling and spray drying of silicon nitride powder; and (2) adapt existing consolidation models to the valve dry-bag isopressing. The objectives of the ICS effort for spray drying were to establish intelligent, closed-loop control of the spray-drying process in order to produce dried spherical silicon nitride agglomerates with: (1) a controllable mean size; (2) narrow size distribution; (3) high CIP density (i.e., minimize agglomerate hardness and the occurrence of dimpled and/or doughnut-shaped agglomerates and internal voids); (4) high flowability; and (5) high yield.

7.2.4.1 Milling Intelligent Control System (ICS).

Sensors corresponding to the three key sensing parameters (pH, temperature, and pumping rate) were made fully operational and communicative with the central computer through FIX DMACS graphic interface software. Programming was completed to allow for communication of corrective signals from the ICS system computer to the three dedicated pumps (to adjust pH, temperature, and pumping rate). These sensors were utilized in a process monitoring mode in preparation of Milling Treatment No's 1 and 2 summarized under the Section 7.2.3 of this report.

7.2.4.2 Spray Drying Intelligent Control System (ICS).

In this area, BDM/MATSYS and NRDC personnel focused on: (1) operation and calibration of the infrared moisture sensor; and (2) development and integration of a fuzzy logic control model with the spray drying ICS.

Early attempts to calibrate the infrared moisture sensor during a series of experiments were unsuccessful. The sensitivity of the optical device to the moisture content of spray-dried silicon nitride powder was demonstrated. However, the measured infrared absorbance ratio of the powder could not be reliably correlated to the actual moisture content measured using standard thermogravimetric techniques.

After reviewing the data from these experiments, BDM/MATSYS identified two potential reasons for the difficulty in calibrating the sensor: (1) an inhomogeneous distribution of moisture within the spray dried agglomerates, and (2) the variation of the focal distance between the sensor and the surface of the powder. Considering the drying mechanisms involved, it is conceivable that moisture gradients exist within individual agglomerates, and that the surface moisture may not be representative of the total moisture content of the powder. If the measured infrared absorbance is a function of surface moisture, it may not be possible to correlate the measured absorbance with the total moisture content of the spray dried powder. A review of the data from the IR sensor recorded on-line also revealed a systematic increase in the measured absorbance ratio over time. The decreasing focal distance between the optical moisture sensor and the surface of the powder as it collects in the bucket below the spray dryer was identified to be a potential cause of the systematically increasing absorbance ratio.

The original installation of the infrared moisture sensor was redesigned to ensure that the focal distance between the sensor optics and the silicon nitride powder collected at the bottom of the spray dryer remained constant. A prototype powder chute was designed and fabricated by BDM/MATSYS for installation at NRDC. As shown in Figure 40, the chute was designed to maintain a relatively constant level of spray dried powder on the lower sloped surface. Fresh powder from the spray dryer is deflected at the top of the chute and cascades down the sloped section and out into a collection bag. A horizontal lip ensures that powder builds up to a thickness several orders of magnitude deeper than the penetration depth of the infrared radiation.

The operation of the powder chute was successfully demonstrated both using previously dried powder and during actual operation of the spray dryer. The powder level within the chute remained relatively constant with maximum variations in height of less than 5 mm. Figure 41 shows the infrared absorbance ratio measured on-line for powder produced at three different slurry flow rates. The on-line measurements are plotted against the moisture content of the collected powder as measured using NRDC's standard thermogravimetric technique. The absorbance ratio and moisture content of the powder are linearly correlated when the variation in focal distance is eliminated.

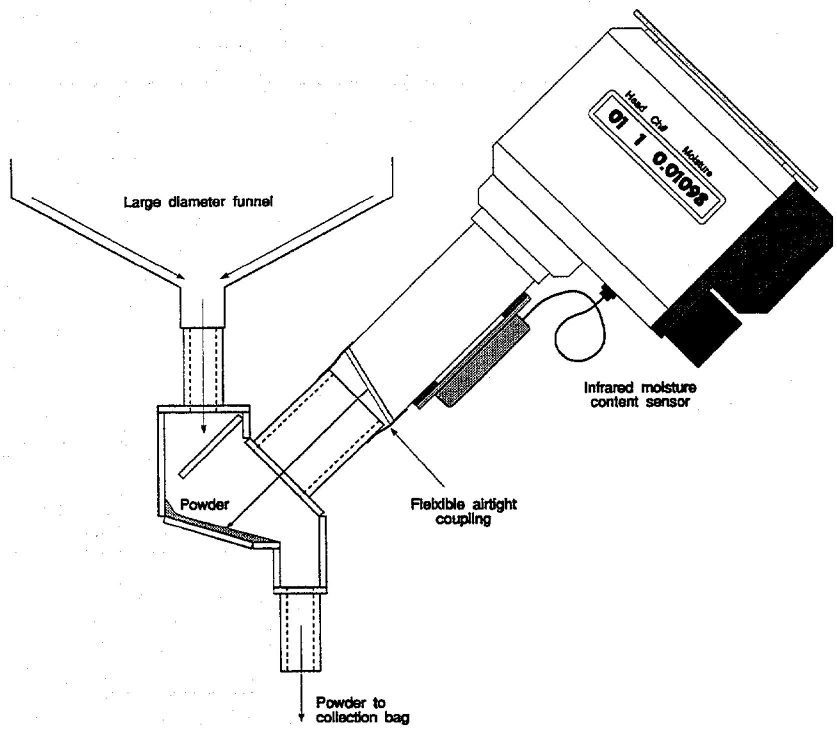
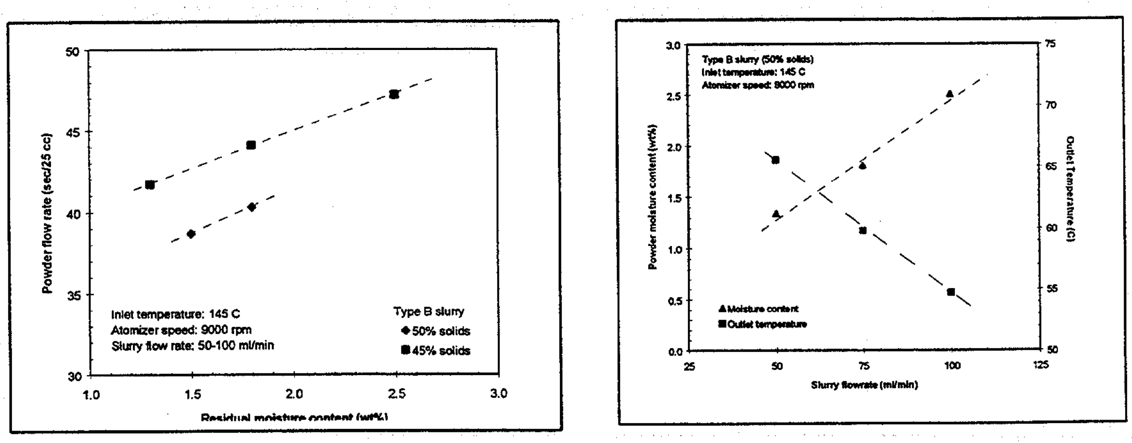


Figure 40. Schematic of Infrared Moisture Sensor on NRDC's Spray Dryer



(A) (B)

Figure 41. (A) Infrared Absorbance as Measured by Kett On-Line IR Moisture Sensor vs Powder Moisture Content Measured by Thermogravimetric Method; (B) Powder Moisture Content vs Slurry Flow Rate.

The data from experiments performed at NRDC were used to develop fuzzy logic control rules that will adjust the slurry flow rate to maintain the powder moisture content at the desired level. The inputs to the controller are the moisture content error (i.e., the difference between the measured moisture and the setpoint), the rate of change of the powder moisture content, and the rate of change of the outlet air temperature. The fuzzy logic control rules were implemented using Cubicalc, a Microsoft® Windows-based fuzzy logic development software package, and were integrated with the FIX DMACS data acquisition and control system using the Dynamic Data Exchange (DDE) feature of Microsoft® Windows. FIX DMACS passes data (e.g., the current slurry flow rate, air temperatures, powder moisture content, etc.) to Cubicalc using DDE. Cubicalc performs the fuzzy logic calculations necessary to calculate the required adjustment to the slurry flow rate. FIX DMACS retrieves the results of this calculation via DDE and sends the required commands to the slurry pump. A schematic of the Intelligent Control System is shown in Figure 42.

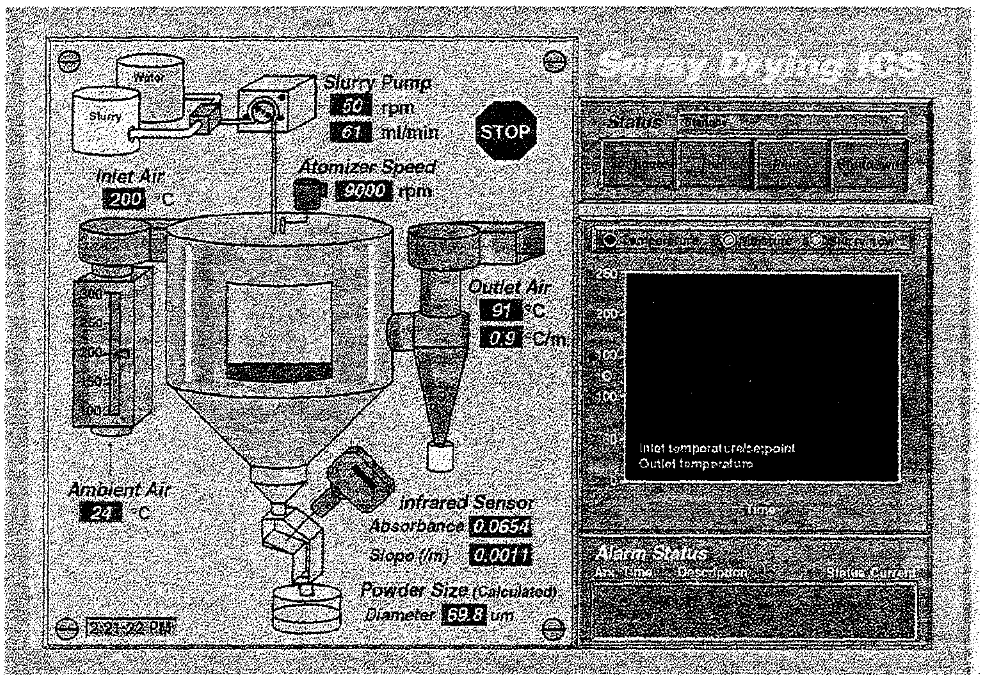


Figure 42. Schematic of The Intelligent Control System

BDM/MATSYS and NRDC personnel also demonstrated closed-loop control of the key spray dried powder attribute, residual moisture content. Figure 43 illustrates the ability of the spray drying ICS to control residual moisture content by varying the slurry flow rate into the dryer. Recommendations from this spray drying system on a larger-diameter production dryer, (2) incorporation of screens before the powder travels by the window of the IR moisture sensor, and (3) utilization of signal conditioning of the powder-moisture-content error signal.

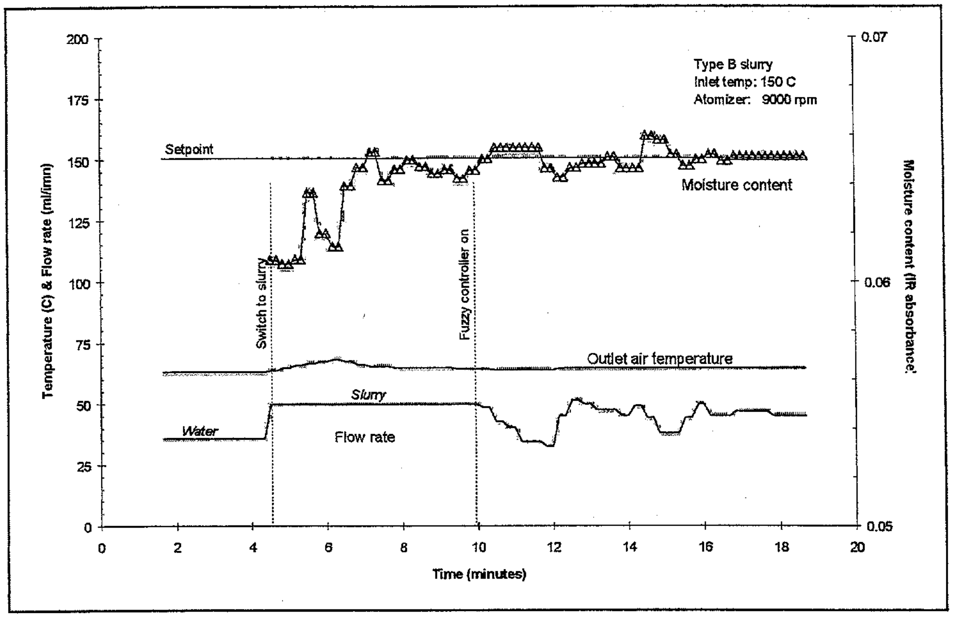


Figure 43. Results of Spray Drying ICS Demonstration

The Intelligent Control System (ICS) for the spray-drying process developed at the Northboro Research and Development Center was transferred to Norton Advanced Ceramic's valve manufacturing facility in East Granby, Connecticut. The basic ICS logic from the small R&D spray dryer to the large manufacturing spray dryer remained the same. However, the electronic hardware and corresponding control logic had to be customized. In this regard, significant assistance was received from MATSYS personnel. The large spray dryer was made operational under full ICS control, and several batches of NT551 powder were successfully produced with the acceptable quality previously established. The large manufacturing spray dryer is currently operational with ICS control.

7.2.4.3 Process Model for Dry-Bag Isopressing.

The objective of this effort was to improve the dry bag isopressing operation used by NAC to form pressed valve blanks from spray dried silicon nitride powder. Advanced process models were used to determine the dry bag geometry and process schedule needed to produce-near-net shape pressed blanks with minimized defects and improved yield. The then-current pressed blanks weighed approximately 220 grams and exhibited defects such as: narrowing of the stem near the initiation of the valve head radius; formation of "elephant's feet" at the ends of around the valve head; and the development of non-uniform density and stress gradients within the pressed part, which lead to warping of the valve stem during the pre-sintering and sintering operations. To compensate for these defects, the pressed blanks must be significantly larger than the final green part, which typically weighs only 80 grams. Pre-sintering and single-point machining are required to remove the large amounts of stock material from the oversized pressed blank. This makes green machining an expensive step in the manufacturing process. Automated single-pass grinding is a more cost-effective approach for forming green parts. However, automated single-pass grinding can only be employed if the pressed blanks are produced with a shape much closer to that of the green part.

MATSYS used the process simulation tools, PDT™ and PROSIM™, to model the dry bag isopressing operation and to guide the design of a new dry bag geometry. The focus of this task was to reduce the occurrence and magnitude of the defects listed above, and to enable the production of a pressed blank significantly closer to the net shape of a green valve.

Process Modeling Tools - PDT™ and PROSIM™.

Although the process of consolidation is continuous, it is helpful to think of consolidation as occurring in sequential stages. The pre-consolidation stage, referred to as Stage 0, is characterized by the powder size distribution, initial packing density (or apparent density), and die geometry. Consolidation includes two stages. In Stage 1, voids within the material are interconnected, and deformation is concentrated at interparticle contacts. As the relative density increases, the interparticle contact area increases until most of the interconnected voids are sealed off. The material, with isolated voids, is now in Stage 2 of consolidation.

Ashby and colleagues [12, 13] have identified three mechanisms that contribute to the densification of porous materials: plastic yielding, power-law creep, and lattice and boundary diffusion. For each stage of consolidation, they have developed a model for each densification mechanism under pure hydrostatic stress. These models were developed for a unit cell (contact between two particles for Stage 1, and a sphere of material containing a concentric spherical void for Stage 2) based on micromechanics principles. As a result, these models are referred to as micromechanics, mechanism-based models.

In addition to hydrostatic stresses, non-hydrostatic stress fields arise during consolidation due to the geometry of the specimen and the density and temperature gradients within the material. The presence of non-hydrostatic stress states necessitates the inclusion of deviatoric stresses in the constitutive laws governing consolidation. MATSYS personnel have worked on the development, implementation, and validation of constitutive models for consolidation of powdered materials subjected to three-dimensional stress states. The micromechanics, mechanism-based models have been implemented in PDT™ and PROSIM™. The numerical integration scheme uses a rate-dependent formulation to allow coupling of all densification mechanisms. It applies to three-dimensional stress states and allows the use of a coupled heat transfer-stress analysis solution algorithm. This software can accurately calculate shape change during consolidation and provide data for graphical representation of the deformed shape at any stage during densification.

PDT™ is a process design tool for developing consolidation process schedules. It can be used to design process schedules for material manufacturing processes including hot and cold isostatic pressing, cold compaction, hot pressing, and sintering. PDT™ uses micromechanics, mechanism-based models to predict the evolution of density during processing and the contribution of various mechanisms to densification. The models correspond to the single stress state which is dominant for a given manufacturing process (such as hydrostatic stress for isostatic pressing and uniaxial stress for cold/hot compaction), and are derived by reducing the models in PROSIM™ to that single stress state. PDT™ provides the capability to interface optimized design schedules and process parameters with an intelligent controller. The process schedules obtained with PDT™ are used as input to PROSIM™ simulations.

PDT™ can be used to examine the mechanisms active during densification, the time during processing in which each mechanism is active, the relative contribution of each mechanism, and the densification rate. In addition, since PDT™ can be executed very quickly and has a user-friendly graphical interface, a parametric study can be performed to examine the effects of different processing conditions, as well as any uncertainty in the material properties on densification.

PROSIM™, PROcess SIMulation, is a finite element-based model used to simulate the consolidation process to determine the final pressed shape of the valve blank and to calculate the density, stress, and strain distributions within the pressed part. The input parameters required by the model include mechanical properties of the spray-dried silicon nitride powder, the mechanical properties of the dry bag material, the geometry of the bag, and the loading conditions during the pressing operation. PROSIM™ can be used to examine the effects of bag geometry and material on the pressed blank; including final shape, density distribution, and stress and strain distributions.

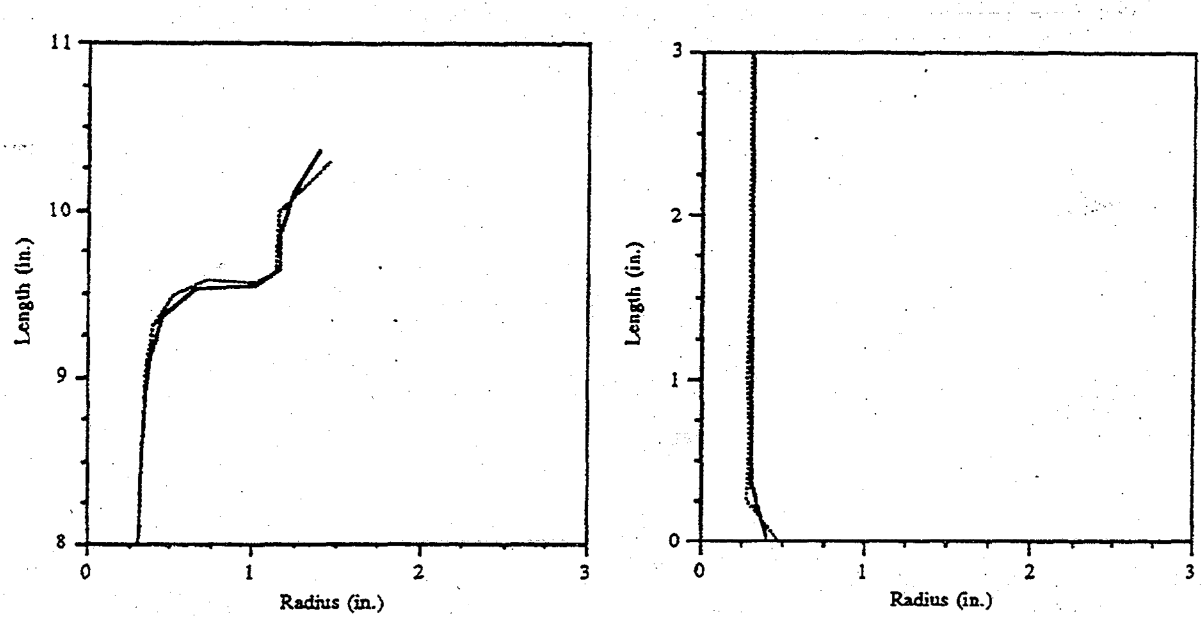
Process Simulation Results.

Simulation of Valve Pressing Operation Using Original Bag. MATSYS personnel received relative density data versus applied pressure from CIP tests performed at the Northboro Research and Development Center (NRDC) for three different batches of spray dried powder. This data was used to determine the "crushing strength" of the agglomerates, an important input parameter for the models. Additional material data was obtained from uniaxial compression tests performed at NRDC. Preliminary estimates of the properties of the dry bag material were made based on data provided by the supplier (Elastomers, Inc.). The geometry of the dry bag and details of the isopressing process schedule were reviewed by MATSYS personnel during a visit to NAC's facility in East Granby, CT.

The finite element mesh used for the simulation is comprised of axisymmetric elements that describe the bag, the powder, and the top and bottom steel rams. The time-dependent loading conditions are applied as pressure on the outside of the bag.

The initial task was to validate the dry bag isopressing model by comparing the results of a PROSIM™ simulation to dimensional measurements taken from a pressed valve blank. The validated model was then used to perform a sensitivity analysis to understand the effects of material properties, dry bag geometry, and loading conditions on the final shape of the pressed blank. The results of this effort were used to design a new dry bag that would produce a near-net-shape pressed blank; minimize defects, such as chipping, narrowing of the valve stem, and the formation of "elephant's feet"; and improve the uniformity of the density and stress distributions within the pressed part.

MATSYS personnel performed a PROSIM™ simulation of the dry bag isopressing operation for the then-current valve blank geometry and process conditions, and compared the results with experimental data from a pre-sintered valve provided by NAC. PROSIM™ was used to predict the shape of the valve after pressing and before sintering. A comparison of the calculated shape of a pressed blank obtained using PROSIM™ and the dimensions of an actual pre-sintered valve blank manufactured at NAC are illustrated in Figure 44. The results of the simulation are in excellent agreement with the experimental data. Small differences between predictions and experimental results are observed at the top of the valve head and at the end of the stem and are due, in part, to the relatively coarse mesh used in the simulation and the sparseness of the dimensional measurements taken from the part.



(a) Valve Head **(b) Valve Stem End**

Figure 44. Excellent Agreement Between Deformed Shape of Pressed Valve Predicted with PROSIM™ (Dotted Line) and from Measurements of a Valve Blank Manufactured at NAC (Solid Line).

The results revealed that there was a significant density gradient in the pressed part. The highest densities were found in the valve stem and the shoulders of the valve head, while the center of the valve head had the lowest pressed density. The results also included hydrostatic and shear stress distributions within the pressed blank. Areas of stress concentration correlated well with observed defects, such as chipping.

First-Iteration Bag Design. With the model successfully validated, PROSIM™ was used to perform several simulations to design a new dry bag that would yield a pressed blank closer to the net shape of a green machined valve. A new geometry proposed by NAC was used as a starting point for the initial redesign of the dry bag. A new simulation was performed, and the final formed shape predicted with PROSIM™ was compared with the green-machined part. An iterative procedure was used to minimize the differences between the predicted final shape of the pressed blank and a green-machined part. The predicted shape and density distribution of a valve blank pressed using the new dry bag geometry are shown in Figure 45. The region of the pressed blank around the seat and shoulder of the valve head was significantly redesigned to reduce the large amounts of excess stock in this area and to improve the uniformity of the density and stress gradients within the blank. This reduces the chipping that occurs around the shoulder of the valve head using the previous bag geometry. A comparison of the pressed blank produced using the new dry bag design and a green machined part is illustrated in Figure 46. As it can be seen, a pressed valve blank formed using the redesigned bag geometry is predicted to be significantly closer to the net shape of the green machined part than a blank formed using the original dry bag. Significant reduction in bag volume was realized with the first-iteration bag design; the new bag has a volume about 40% smaller than its predecessor. In addition, the density gradients between the shoulders and center of the valve head are reduced.

Valve Pressing Operation Using First Iteration Bag Design. A new dry bag with the new geometry was fabricated and used to press valve blanks to demonstrate the first-iteration improvements in the isopressing process. Using this first-iteration bag, NAC pressed valve blanks using powder prepared by two methods. The powders are herein referred to as Slurry Type A Powder and Slurry Type B Powder.

While significant differences were observed between valve blanks pressed with Type A and Type B powders, major improvements were obtained with the first-iteration bag. This bag geometry significantly reduced the occurrence of chipping around the valve head, but revealed significant narrowing of the valve stem, especially in blanks pressed from Type B powder. The severe narrowing is attributed, in large part, to the powder. This bag was designed for the powder made using NAC's prototype process. However, in the course of the ACMT program the processing of the powder was modified. Significant differences in loose powder densities were observed between the powder made using NAC's prototype process (0.95 g/cc), Type A powder (1.08 g/cc) and Type B powder (0.91 g/cc). In addition, significant differences in pressing response were observed for these powders.

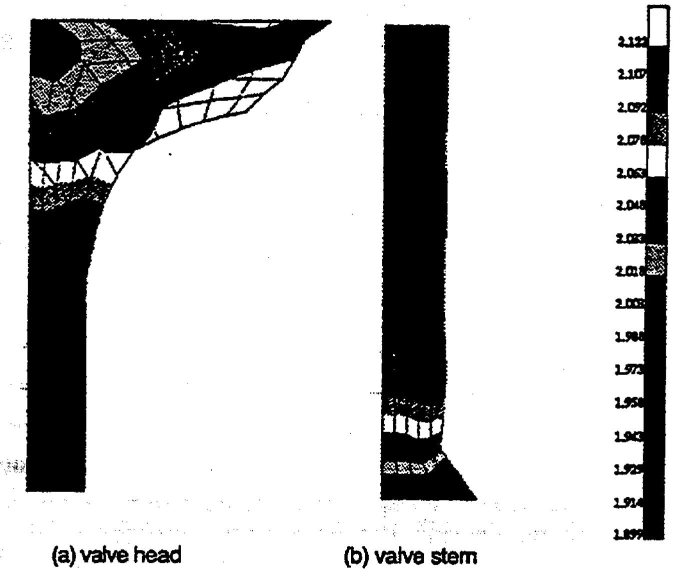


Figure 45. Final Deformed Shape and Density Distribution (g/cc)
(Predicted Using PROSIM™ for First-Iteration Dry Bag Design)

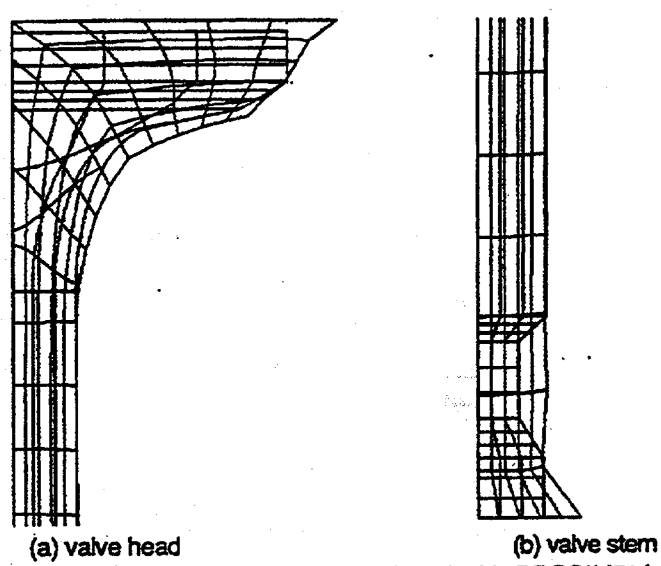


Figure 46. Comparison of the Final Deformed Shape
(Predicted with PROSIM™ for the First-Iteration Dry Bag Design with the Shape of a Green Machined Valve)

MATSYS personnel received pressing data versus applied pressure from tests performed at NRDC for the Type A and Type B powders. This data was used to determine the crushing strength of the agglomerates. The properties of the dry bag material were the same as those used in the initial analysis. A drawing of the bag was provided by NAC personnel.

Because of the significant differences in the properties of powder types A and B, different bag designs were required for near-net-shape forming with each type powder. Therefore, simulations were performed for both powder types. Before a new bag design was completed, the Type A powder was selected for valve manufacturing. As a result, only results for this powder are discussed, and a second iteration bag design is illustrated.

Second-Iteration Bag Design For Type A Powder. The same approach described above for the first iteration bag design was used to design a new bag for Type A powder. A simulation was performed for the pressing operation using the first-iteration bag design, and the results were compared with measurements on pressed blanks provided by NAC personnel. The bag geometry was then modified to yield a pressed shape closer to a green-machined valve than could be obtained with the current bag.

NRDC personnel provided powder compaction data, the amount of powder required to fill the bag, and dimensional measurements of pressed valve blanks using the first-iteration bag design. The compaction data was used to determine the crushing strength of the agglomerates, an important input parameter for the models. For Type A powder, the crushing strength was estimated to be 175 MPa. The powder packing relative density was estimated to be 0.333. The initial task was to compare the results of a PROSIM™ simulation to dimensional measurements taken from a pressed valve blank made out of Type A powder. The objective of this task was to validate the model and investigate the problems observed during the pressing operation. Emphasis was placed on correctly capturing the narrowing of the valve stem.

A finite element mesh was generated. The mesh was comprised of axisymmetric elements that describe the bag, the powder, and the top and bottom steel rams. The elements describing the interior of this bag are shown in Figure 47. The time-dependent loading conditions were applied as pressure on the outside of the bag.

The calculated pressed blank was in good agreement with the measured dimensions of an actual pressed valve blank manufactured at NAC. The model captured the narrowing in the stem observed in the pressed valve blanks. This bag geometry reduced the stress and density gradients within the pressed blank and especially within the valve head. As a result, the chipping observed when the old bag was used was reduced significantly. No significant density gradients were observed in the valve stem. The major defect observed was narrowing of the stem. The task was to modify the design to eliminate narrowing of the stem and further reduce the amount of powder required for valve fabrication.

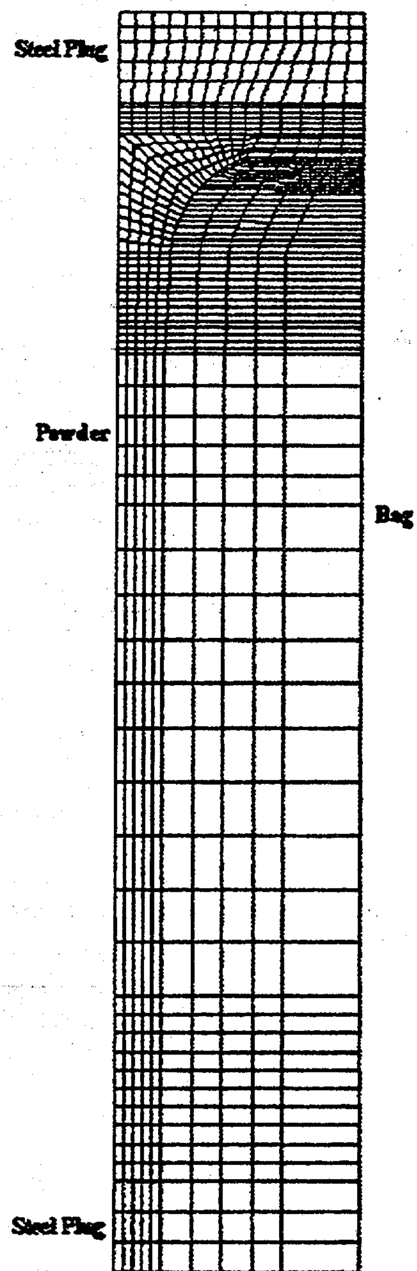
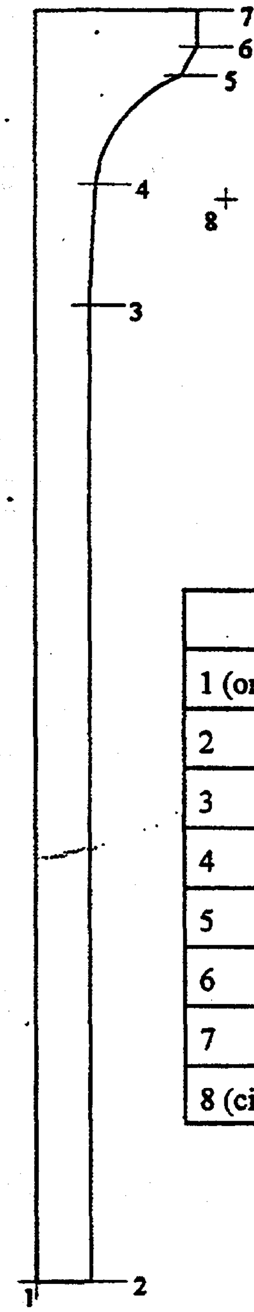


Figure 47. Finite Element Mesh Used for Modeling Isobag Pressing and Bag Design
(The mesh consists of axisymmetric elements describing powder, bag, and steel plugs.)

Two major modifications were made in the design. First, a sloped region was introduced to transition from the valve stem to the valve head. The slope was designed to eliminate narrowing of the stem. Second, the valve-head area was modified to minimize the amount of powder required to fill the bag.

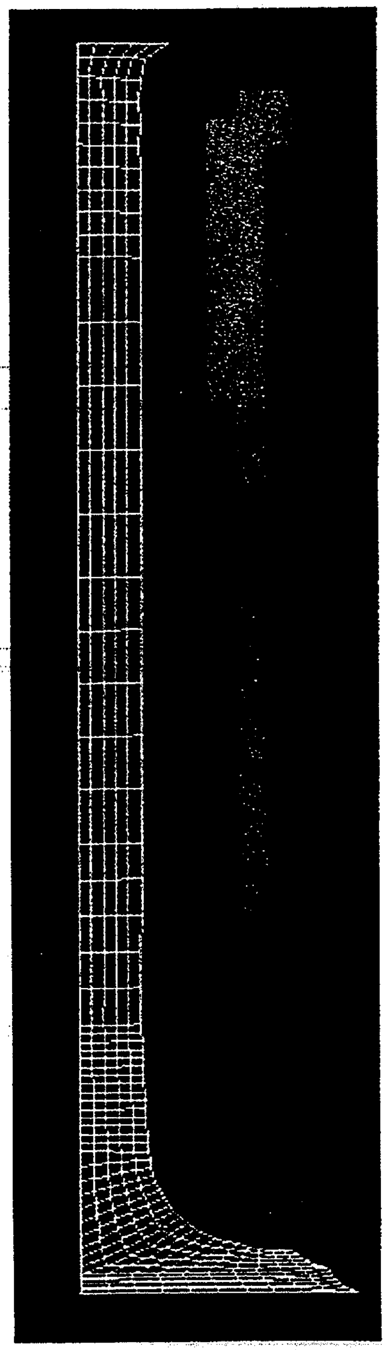
An iterative procedure was used to arrive at the final bag geometry, and a simulation was performed. The deformed shape obtained through simulation was compared with the desired green-machined shape that was provided by NAC personnel. The bag design was then modified to minimize the discrepancies observed between the calculated shape and the green-machined shape. Several iterations were performed. The final bag geometry, with a volume 44% smaller than the original bag, is illustrated in Figure 48.

The results for the final bag design are illustrated in Figures 45 through 47. The deformed shape after pressing is illustrated in Figure 49. The predicted deformed shape following isobag pressing lies just outside the green machined shape, as illustrated in Figure 50. The density distribution is illustrated in Figure 51. The highest densities are found in the valve stem and the shoulders of the valve head while the center of the valve head has the lowest pressed density. The results also include hydrostatic and shear stress distributions within the pressed blank, illustrated in Figure 52 and Figure 53, respectively. Areas of shear stress concentration and low hydrostatic stress are in the shoulder of the valve head and are the areas most likely to chip. These areas are machined in the green machining stage. The stress gradients are reduced from those observed when the original bag was used.

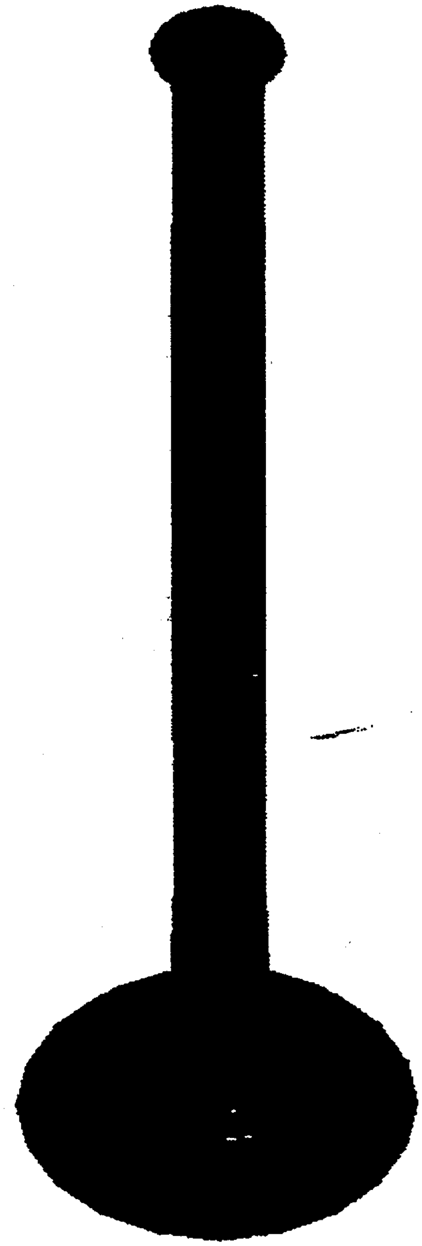


Point	X (in)	Y (in)
1 (origin)	0.000	0.000
2	0.454	0.000
3	0.454	8.055
4	0.506	9.055
5	1.224	9.963
6	1.356	10.198
7	1.356	10.500
8 (circle's center)	1.59332	8.9332

Figure 48. Geometry for the Second-Iteration Bag Design



Axisymmetric cross-section



(b) 3-D shape

Figure 49. Valve Shape Following Isobag Pressing

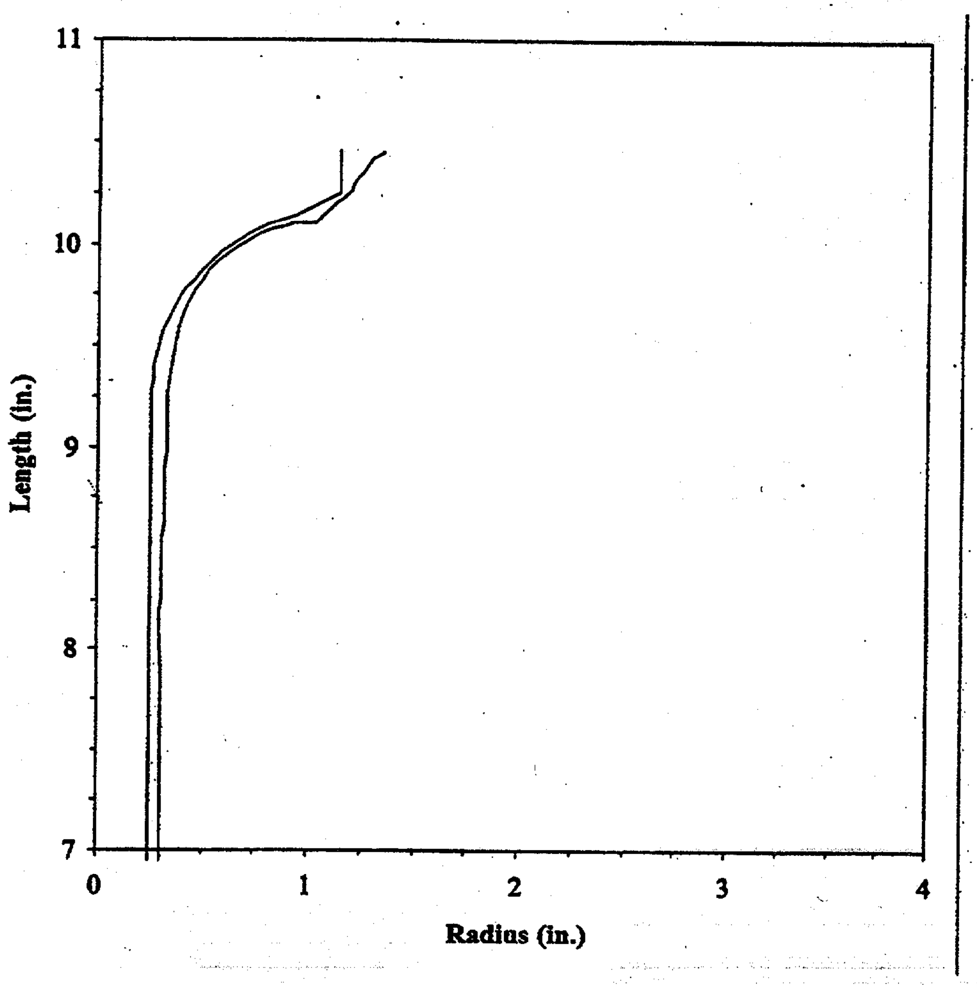
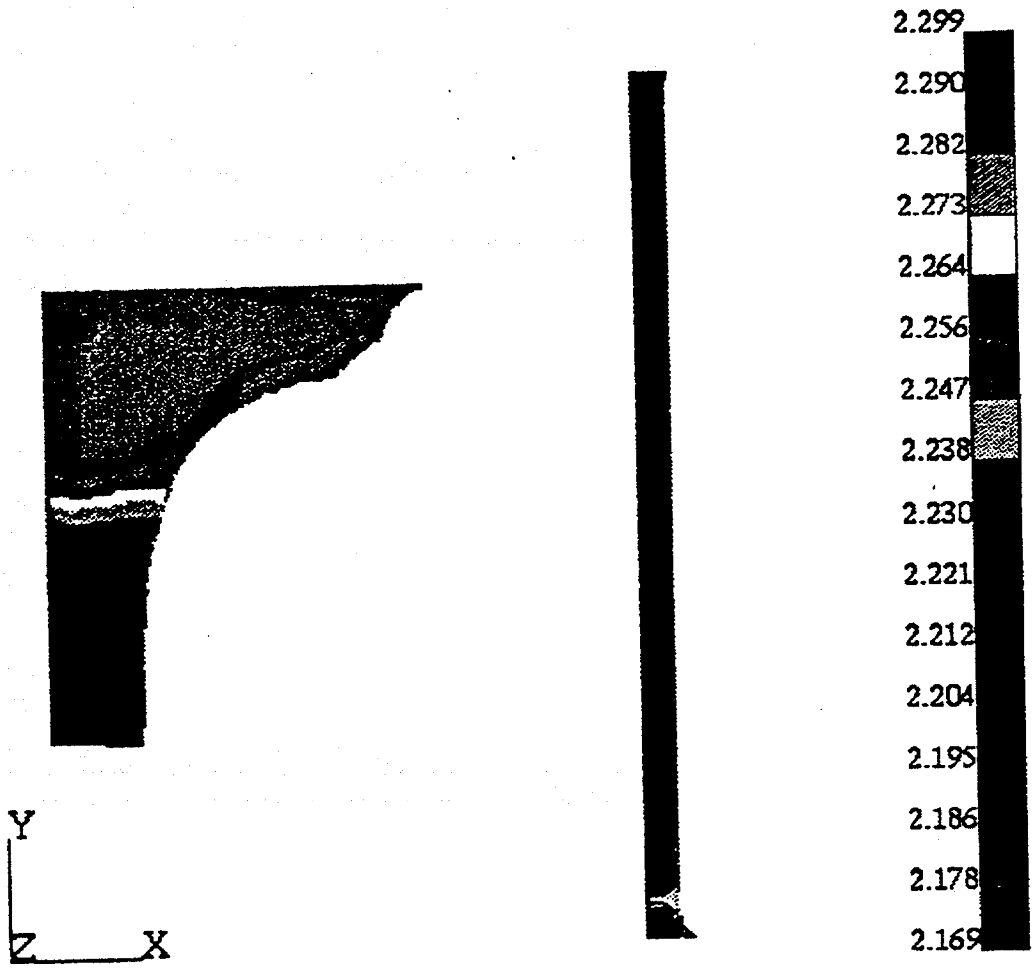


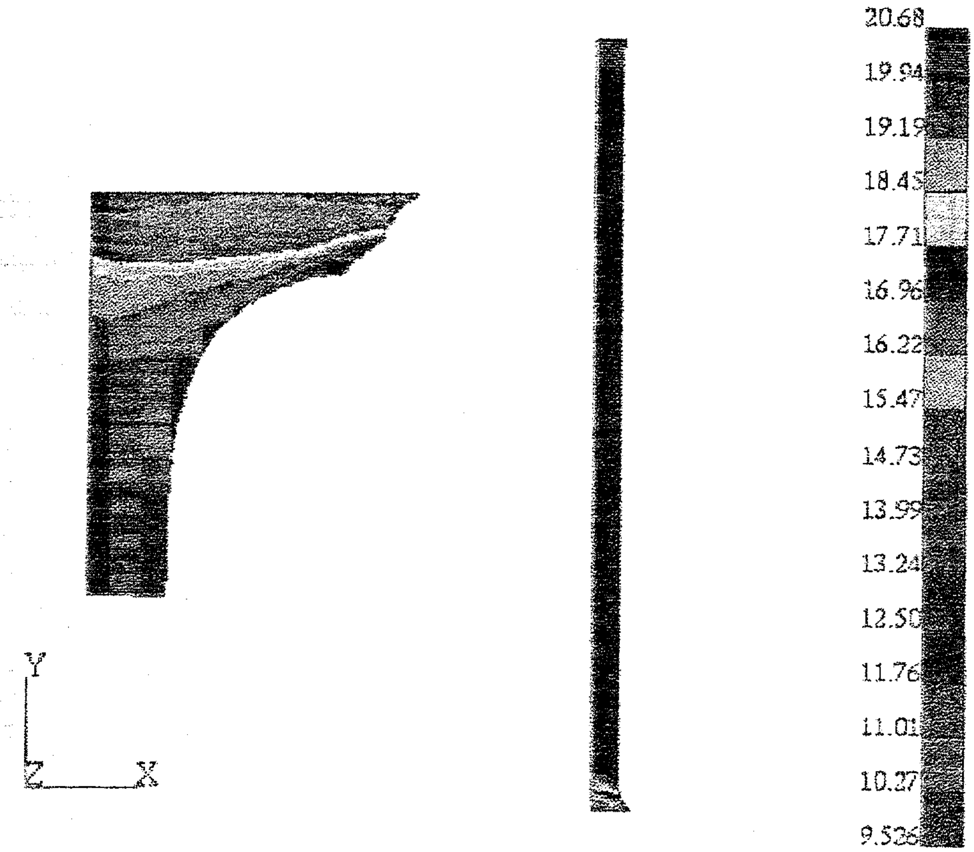
Figure 50. The Predicted Deformed Shape Following Isobag Pressing
(With second-iteration bag design lies outside the green machined valve.)



(a) Valve head

(b) Valve Stem

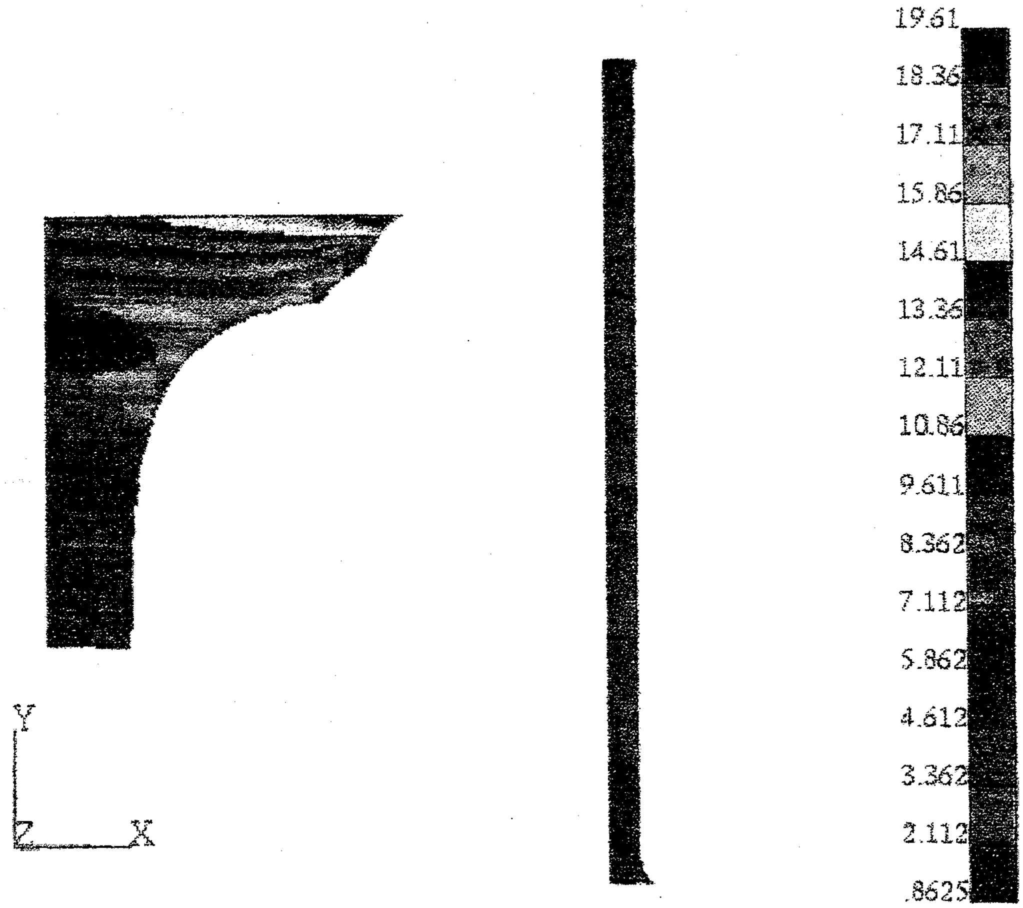
Figure 51. Density Distribution (g/cc) within Valve Following Isobag Pressing



(a) Valve head

(b) Valve Stem

Figure 52. Hydrostatic Stress Distribution (Ksi) within Valve Following Isobag Pressing



(a) Valve head

(b) Valve Stem

Figure 53. Shear Stress Distribution (Ksi) within Valve Following Isobag Pressing

7.3 INSPECTION AND TESTING - TASK 3

A total of 160 finished NT451 SiAlON Series 149 valves were provided to DDC (80 with a 30°-seat-angle, 80 with a 45°-seat-angle). Vacuum checking of the 30°-seat-angle ceramic valves was performed in accordance with DDC Specification 67T-2, "Intake and Exhaust Valve Sealing Test Procedure." All 80 of the valves met the specification. NAC's dimensional inspection data for all of the valves was provided to and reviewed by DDC as part of their receiving inspection.

A complete package of raw data generated from NAC's testing in accordance with DDC Specification 15T-4/SI49, "Engineering Product Approval Requirements for Experimental SiAlON Exhaust Valve," was provided to DDC. Except for fracture toughness, a review of mechanical and physical properties, grain size, aspect ratio, porosity, phase assemblage, and proof-test data for each batch of valves indicated compliance with the DDC material specification. The fracture toughness requirement was subsequently met, along with all other properties, by replacing NT451 SiAlON with the more cost effective NT551 silicon nitride as described in Section 7.2.3.1.

Twenty seven of the eighty 30°-seat-angle valves delivered to DDC were forwarded to ORNL for fatigue testing.

A 6V-149 overhead fixture was assembled with fourteen 30°-seat-angle ceramic valves, eight 45°-seat-angle ceramic valves, and two production metal valves. The seat inserts were checked for runout and were repaired as necessary to remain within a specification of 0.002 in. Valve guide IDs were measured and recorded for this test. Initial testing at 1,900 rpm for 100 hours was completed with no valve failures. Additional overspeed tests at 2,100 rpm, 2,500 rpm, and 3,000 rpm were performed. The overspeed tests at 2,100 rpm and 2,500 rpm were suspended after 200 hours with no failures. The 3,000-rpm test ended at 23 hours with breakage in a total of five of the 16 valves tested. The following observations were made upon inspection of the failed valves:

1) Two failure modes were present. Two of the five failures were in the stem just above the underhead radius, and three were in the lock groove.
2) A higher percentage of 45°-seat-angle valves failed (3 of 8) as compared to the 30°-seat-angle design (2 of 14). None of the 30°-seat-angle valves failed in the stem.
3) Visual examination of the three valves that failed in the lock groove revealed severe chipping at the lock groove-stem OD intersection (tip side only). These were the only valves that exhibited this chipping. Visual examination of the copper-coated locks for these components showed contact with the ceramic valve only in two narrow regions 180° apart, which coincided with the seams in the two-piece lock. This observation provides evidence that the locks distorted to the point where contact stresses became high enough to induce chipping and eventual breakage of the valve through the lock groove.

Despite these failures, DDC's minimum overspeed testing requirement of 20 hours at 3,000 rpm was met. Completion of the overspeed fixture testing was performed in fulfillment of NAC's ACMT Milestone No. 4. Engine durability testing of these preliminary design valves, as an activity beyond the scope of the Milestone No. 4 requirements, was initiated later during the program as described below.

Scanning electron microscope (SEM) analysis of the valves that had failed on the overspeed fixture test was conducted at the High Temperature Materials Lab (HTML) at ORNL under the User Program. Keeper-groove failures were induced by the deterioration of the keeper. Softer keepers were incorporated to eliminate this problem completely. Stem failures were bending-related with the failure plane being parallel to the grinding marks on the stem surface. As described in the machining subtask (Task 2c), a modified machining procedure was implemented by Vendor C such that grinding marks were aligned approximately parallel to the valve-stem length. This completely eliminated valve stem failure due to grinding marks.

Air flow testing of 30°-seat and 45°-seat ceramic valves was conducted and compared to baseline air flow rate (Figure 54). The 30° valves showed flow rates very close to baseline. However, the flow rate of the 45° valves was lower than baseline at low lifts, where the good flow rate is especially important, and better than baseline for high lifts.

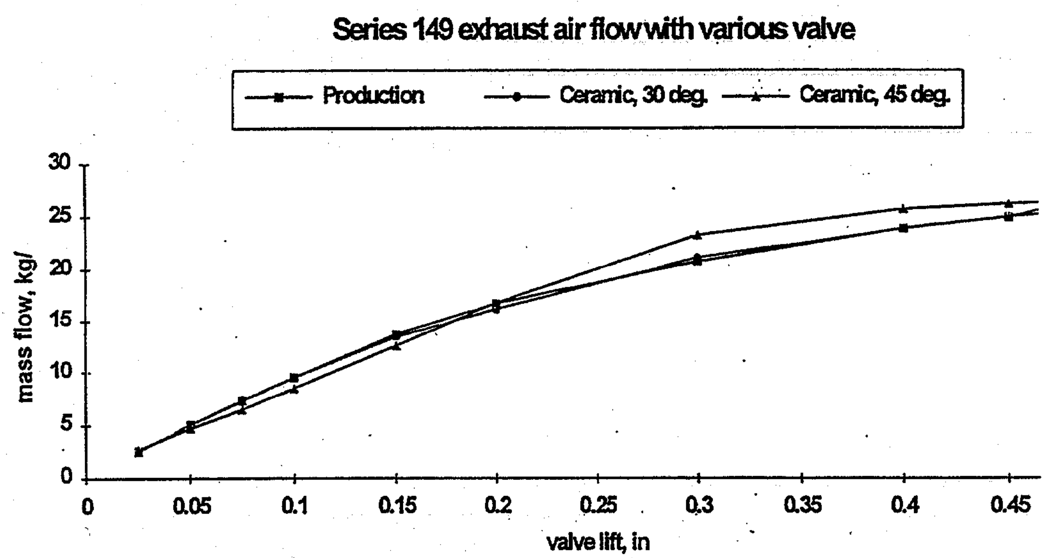


Figure 54. Air Flow Testing Results

Dynamic modeling of the Series 149 valve train was performed at DDC using ADAMS software. The cam, rocker arm with adjusting screw, and valve bridge were modeled with their appropriate boundary conditions. This model has been simulated kinematically to verify cam lift, velocity, and acceleration. The ADAMS kinematics results were identical to DDC's available spreadsheet results. Intermittent contact, which allows for separation of the follower from the cam during high-cam-speed motion, was modeled. This baseline model was used to predict the dynamic characteristics of ceramic valves. Figure 55 depicts improvements in valve train dynamics at 1900 rpm due to the lower ceramic valve weight, which include:

- A 300 rpm increase in engine speed before reaching zero valve spring force (an indication of overspeed capability).
- A 146 lb force decrease at peak load on the rocker arm during valve opening.
- A 223 lb force decrease at peak load on rocker arm during closing.

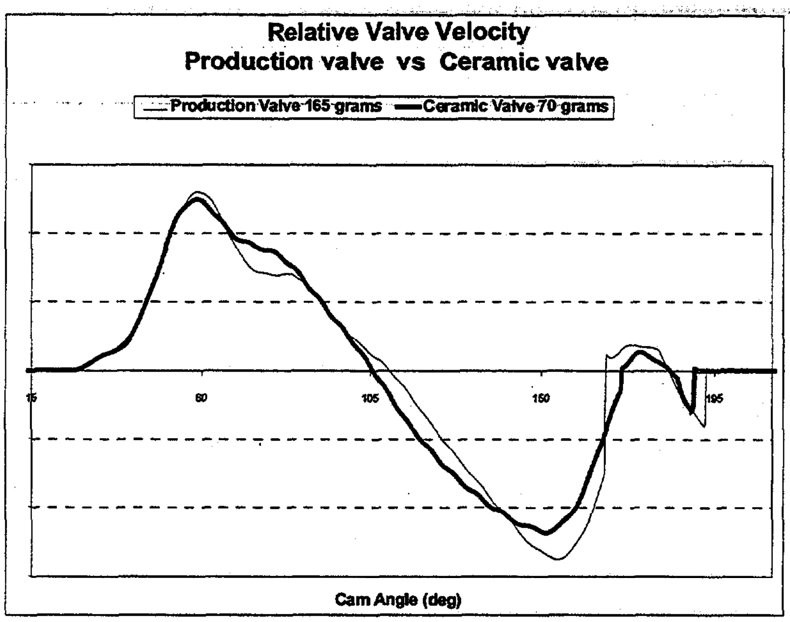


Figure 55. Valve Train Modeling Results

Based upon the above results, the cam profile should be modified in order to take advantage of these improvements.

An 8V-149 engine was built at DDC's Redford manufacturing plant. The engine was assembled with thermocouples and other instrumentation. Sixteen 30°-seat and sixteen 45°-seat ceramic valves were assembled in eight cylinder heads. These cylinder heads were provided to the production facility to be used during the engine assembly. The serial numbers of the valves were recorded in relation to each valve's position in the engine. The engine calibration was modified to correspond to the highest power rating available in production for the Series 149 engine. The 8V-149 engine with thirty-two ceramic valves was then subjected to the mine-haul-truck durability cycle. As required, a five-hundred-hour durability test of the ceramic valves was completed without any incident. The valves were removed from the cylinder heads and were analyzed at DDC's Materials Laboratory.

Upon removal of the valve springs and valves from the heads, one of the valves in position 3R was found with the tip of the valve fractured off. The valve did not drop during the engine test because both the tip and the valve were retained by the keeper.

Although the retention of the broken valve is a good indication for field operation, it prevented earlier discovery of the failure. DDC returned the valve to NAC for additional analysis. Following analysis, it was concluded that the use of the NAC-design machined keepers and/or the soft DDC keepers may help minimize the stress concentration inside the groove by providing a better fit. Consequently, NAC initiated an additional 500-hour test at DDC to evaluate the two keeper designs.

A split set of 30° ceramic valves was installed in an 8V-149 engine for the additional five-hundred-hour, mine-haul-cycle durability test. Some valves had the soft keepers from Milwaukee Wire, while the other valves had the NAC-design machined keepers.

At 250 hours, valve inspection was conducted. The cylinder heads were pulled out of the engine and the valves were removed from the cylinder heads. All valves and keepers were inspected. The valve faces and seat surfaces looked fine. Some wear marks on the keepers were detected, but were within the expected range. The engine was reassembled and the test resumed. An additional 250 hours were accumulated on these valves.

Thus, a second five-hundred-hour test was completed. At the end of the test, all cylinder heads were removed from the engine and disassembled. All ceramic valves were in excellent condition, with no signs of wear on the seat or in the keeper-groove area. Some soft deposits were found on the combustion faces of the valves, as would be expected. All keepers were found to be in good shape, with some wear marks corresponding to the upper edges of the keeper groove on the valves. The wear marks on both the soft and machined keepers were very similar.

Based on the above test results, the valve design was finalized. The final design incorporated a 30° seat angle and a keeper groove with the chamfer on the bottom side and a radius on the top side. In addition, DDC's soft keepers were selected over production keepers.

With the final valve design established and incorporated into the cost-effective machining development campaign for NT551 silicon nitride valves, the following four machining vendors were engaged so that their respective machining approaches could be evaluated.

Vendor A – High Speed CNC Machining
Vendor B – Centerless Profile Grinding
Vendor C – Compound Centerless Grinding
Vendor D – Peel Grinding

The quality and cost effectiveness of the machining procedures were assessed by dimensional measurement and machining time, respectively. The quality assurance involved detailed dimensional measurement at various locations of the valve by both NAC and DDC, as well as pull testing. The machining time for the various machining procedures was fed into the cost model developed by IBIS to arrive at the final cost of machining. A number of valves from the production demonstration set, sufficient to perform the below described durability testing, was supplied to DDC.

Following the receipt of 33 Vendor-A-machined valves, and after visual inspection, a process-capability evaluation was conducted at DDC. The valves were seal tested at DDC Receiving Inspection; a vacuum of 77.89 kPa (23 in.Hg) was applied in a test cylinder fitted with a test valve. After a 10-second delay, the vacuum loss in the cylinder was measured. All valves passed the test.

A similar procedure was followed upon receipt of 15 Vendor-D-machined valves. Of these 15 valves, only 1 was within DDC specifications. Further, one valve did not pass the sealing test. NAC had previously conducted pull testing and had caused chipping above the keeper groove or on the valve seat of 7 valves. The chipping is believed to have caused this one valve to fail the sealing test.

The statistical results of the dimensional measurements are summarized following in Table 31 and Table 32. In both tables, Capability Index (a measure of process control) equals the tolerance range ÷ 6 σ, where σ is an estimate of standard deviation based on the measured data. The location numbers in the Table 31 correspond as follows:

Loc. 8: Combustion Face Diameter
Loc. 10: Half of Valve Seat Height to Stem End
Loc. 11: Half of Valve Seat Height to Middle of Keeper Groove
Loc. 12: Combustion Face Height to Half of Seat Height
Loc. 13: Combustion Face Height to Arbitrarily Chosen Point on Fillet
Loc. 14: Surface Finish (Seat)
Loc. 15: Surface Finish (Stem)
Loc. 16: Surface Finish (Stem)
Loc. 17: Surface Finish (Keeper)

Table 31. Dimensional Statistics of Vendor A Valves

valve #	dry mass (g)	wet mass (g)	Density (g/cm³)	loc. 1 (in.)	D1 (in.)	D2 (in.)	D3 (in.)	D4 (in.)	D5 (in.)	D6 (in.)	D7 (in.)	loc. 8 (in.)	loc. 10 (in.)	loc. 11 (in.)	loc. 12 (in.)	loc. 13 (in.)	loc. 14 (in.)	loc. 15 (in.)	loc. 16 (in.)	loc. 17 (in.)
177213397	71.71	49.98	3.293	0.2797	0.3396	0.3397	0.3398	0.3397	0.3397	0.3396	0.3395	1.7984	7.4043	6.898	0.142	0.2955	6.5	4.5	4	5
177513397	71.64	49.93	3.293	0.2792	0.3393	0.3395	0.3397	0.3398	0.3399	0.3396	0.3397	1.7987	7.4003	6.894	0.1436	0.2971	4	7.3	7.3	4
188513397	71.68	49.96	3.293	0.2817	0.3396	0.3397	0.3397	0.3398	0.3399	0.3398	0.3396	1.7995	7.3982	6.893	0.1425	0.296	4	7.4	7.8	5.34
189813397	71.56	49.89	3.295	0.2782	0.3394	0.3395	0.3395	0.3395	0.3396	0.3396	0.3394	1.9881	7.4004	6.897	0.1457	0.2992	4	8.2	8.3	5.3
189913397	71.48	49.83	3.295	0.28	0.3396	0.3396	0.3398	0.3397	0.3397	0.3396	0.3396	1.799	7.3989	6.896	0.1451	0.2986	4	7.8	7.5	5.3
1.81E+09	71.74	50.01	3.294	0.2793	0.3396	0.3396	0.3399	0.3398	0.3399	0.3397	0.3395	1.7987	6.9498	6.894	0.1492	0.2927	4	4.6	4.2	6.4
19113397	71.48	49.79	3.289	0.2781	0.3398	0.3399	0.3397	0.3396	0.3396	0.3396	0.3398	1.7976	7.4014	6.898	0.1439	0.2974	4	4.7	4.3	5.4
19313397	71.67	49.92	3.288	0.2777	0.3395	0.3396	0.3398	0.3399	0.3399	0.3397	0.3395	1.7983	7.403	6.898	0.1458	0.2993	4	7	7.2	6.3
19513397	71.77	49.99	3.288	0.2779	0.3396	0.3396	0.3399	0.34	0.34	0.3399	0.3398	1.7982	7.3972	6.892	0.1451	0.2986	4.5	5.9	5	4.9
19613397	71.78	50	3.289	0.2793	0.3394	0.3395	0.3397	0.3399	0.3399	0.3398	0.3397	1.7983	7.3961	6.896	0.145	0.2985	4.5	4	5	5.9
19713397	71.74	49.97	3.288	0.2779	0.3395	0.3396	0.3397	0.34	0.34	0.3398	0.3395	1.798	7.3994	6.896	0.1432	0.2967	4.5	5	5	4.5
19813397	71.68	49.92	3.287	0.2777	0.3396	0.3396	0.3397	0.3398	0.3398	0.3398	0.3397	1.7976	7.4025	6.898	0.1455	0.299	4.5	5	5	6.2
19913397	71.71	49.96	3.29	0.2778	0.3398	0.3397	0.3396	0.3396	0.3396	0.3396	0.3395	1.7972	7.4002	6.894	0.1457	0.2992	5	3.7	3.3	7
191013397	71.61	49.88	3.288	0.2777	0.3397	0.3397	0.3397	0.3397	0.3396	0.3396	0.3397	1.7961	7.3984	6.896	0.1466	0.2901	4.5	2.9	3.4	4.2
191113397	71.65	49.91	3.289	0.2781	0.3396	0.3397	0.3397	0.3397	0.3399	0.3397	0.3395	1.7967	7.4011	6.898	0.1451	0.2986	4.5	4	3.8	5.5
191213397	71.5	49.81	3.289	0.2779	0.3397	0.3397	0.3396	0.3395	0.3396	0.3396	0.3395	1.7967	7.3994	6.895	0.1454	0.2989	6	5	3.5	5.8
191313397	71.49	49.8	3.289	0.2774	0.3396	0.3396	0.3395	0.3396	0.3396	0.3396	0.3395	1.7967	7.4002	6.898	0.1444	0.2979	4.5	4.6	4	6
191413307	71.65	49.9	3.287	0.2788	0.3396	0.3396	0.3396	0.3396	0.3396	0.3395	0.3395	1.797	7.3934	6.897	0.1458	0.2993	5	7	6	5.4
191513397	72.21	50.29	3.287	0.2782	0.3399	0.3399	0.3398	0.3398	0.3398	0.3396	0.3397	1.7963	7.4007	6.896	0.1456	0.2991	4	7	7.5	5.4
191613397	71.53	49.82	3.288	0.2783	0.3398	0.3397	0.3396	0.3396	0.3396	0.3394	0.3394	1.7977	7.399	6.896	0.1446	0.2981	6	6.5	7.5	4.5
191713397	71.63	49.89	3.288	0.2784	0.3399	0.3399	0.3398	0.3397	0.3397	0.3396	0.3396	1.7977	7.3997	6.886	0.1425	0.296	4.5	8.5	8.5	4.7
191813397	71.49	49.79	3.287	0.2788	0.3395	0.3395	0.3395	0.3394	0.3393	0.3392	0.3392	1.7975	7.3988	6.89	0.1437	0.2972	4	8.5	8	4.7
192113397	71.51	49.8	3.287	0.2776	0.3396	0.3396	0.3396	0.3396	0.3396	0.3396	0.3396	1.7977	7.4026	6.899	0.1451	0.2986	5	6.5	6	4.9
192413397	71.6	49.87	3.288	0.277	0.3396	0.3394	0.3393	0.3392	0.3392	0.3391	0.3392	1.796	7.3959	6.89	0.1446	0.2981	5	8.5	8	4.9
193913397	71.64	49.89	3.287	0.283	0.3397	0.3397	0.34	0.3398	0.3398	0.3396	0.3395	1.7982	7.4013	6.896	0.143	0.2965	5	3.5	4	6.3
194013397	71.59	49.86	3.288	0.2779	0.3398	0.3399	0.3399	0.3399	0.3399	0.3399	0.3398	1.7995	7.4007	6.896	0.1425	0.296	5.5	4.5	5	5.8
194113397	71.44	49.74	3.285	0.28	0.3396	0.3396	0.3396	0.3394	0.3395	0.3396	0.3397	1.7989	7.4033	6.897	0.1448	0.2983	6	4	3	7.7
19A13397	71.58	49.86	3.289	0.28	0.3398	0.3398	0.3396	0.3396	0.3398	0.3396	0.3398	1.798	7.4028	6.894	0.1425	0.296	6.5	6.5	8	7.4
19B13397	71.54	49.82	3.287	0.2782	0.3396	0.3397	0.3397	0.3396	0.3398	0.3398	0.3398	1.7977	7.3984	6.895	0.1436	0.2971	6	5.5	6	6.3
19C13397	71.45	49.76	3.287	0.2786	0.3397	0.3397	0.3396	0.3393	0.3394	0.3394	0.3393	1.7977	7.4046	6.9	0.1445	0.298	6	4	4	7
19E13397	71.46	49.78	3.289	0.2787	0.3395	0.3396	0.3395	0.3394	0.3394	0.3393	0.3393	1.798	7.4009	6.9	0.1445	0.298	4.5	7	7	7.5
19G13397	71.52	49.91	3.287	0.2785	0.3397	0.3398	0.3395	0.3395	0.3396	0.3396	0.3397	1.798	7.395	6.895	0.1454	0.2989	5.5	3.5	4	7.8
19H13397	71.6	49.86	3.286	0.2794	0.3397	0.3397	0.3396	0.3396	0.3397	0.3396	0.3397	1.7979	7.3963	6.894	0.1425	0.296	7	3	4	7
std. dev.	0.144805	0.1024	0.00259	0.001237	0.0001	0.0001	0.000146357	0.0002	0.0002	0.0002	0.0002	0.0331	0.07838	0.00296	0.0015	0.00197	0.885	1.7351	1.784	1.04
average	71.616	49.891	3.289	0.279	0.340	0.340	0.340	0.340	0.340	0.340	0.340	1.804	7.386	6.896	0.145	0.297	4.924	5.624	5.609	5.768
			tolerance width (in)	0.01	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.01	0.01	0.015	0.009	0.01				
			capability index (%)	135	96	107	91	69	68	75	78	5	2	84	101	85				

Table 32. Dimensional Statistics of Vendor D Valves

Location Measured	Axial Run-Out Valve Tip	Diameter Groove	Radial Run-Out Groove	Diameter Valve Stem End	Stem Diameter Valve Tip	Stem Diameter Valve Head	Shoulder Height Valve Head
Capability Index	**19.75%**	**426.18%**	**114.04%**	**36.46%**	**47.43%**	**37.38%**	**69.75%**

Location Measured	Radial Run-Out Valve Seat	Diameter Valve Profile	Diameter Valve Head	Axial Run-Out Plate Valve Head	Total Length	Distance Groove/Valve Head Plan Face
Capability Index	**16.28%**	**84.17%**	**185.30%**	**84.86%**	**19.55%**	**125.88%**

7.3.1 Overhead Fixture Test

This fixture was intended to be run without fuel; a dynamometer was used to motor the engine, thereby driving the oil pump and camshafts. The fuel pump was unhooked, but the injectors were left in place. The injector rocker arms were cut to serve as spacers, and the rocker oil passages were plugged. Sixteen NT551 ceramic valves were installed on the fixture; eight originating from Vendor A and eight from Vendor D. The valve lash was set to 0.2 mm (0.008 in.) and 0.7 mm (0.028 in.) for ceramic and production valves, respectively. An automatic shutdown system was set-up, which was designed to cut the dynamometer power if the oil temperature rose higher than 116°C (240°F), or if the oil pressure dropped below 68.95 kPa (10 psi).

The fixture was run for 100 hours at 1900 rpm and 106 hours at 2100 rpm. The first valve inspection was conducted at 53 hours with no major problems detected. The fixture layout is shown below in Figure 56.

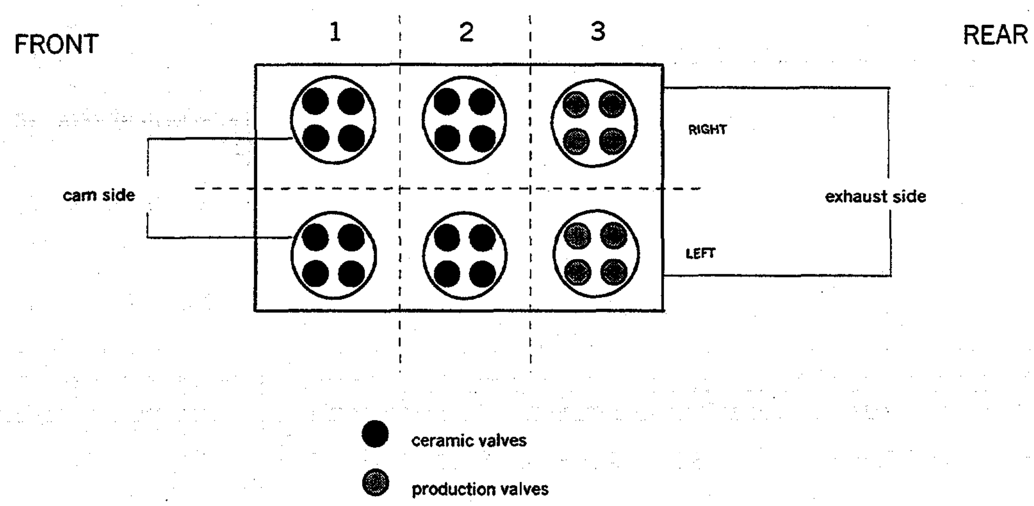


Figure 56. Overhead Fixture Layout

7.3.2 Engine Durability Tests

The engine durability tests were performed only on the valves that were machined using the techniques selected from initial screening trials. As described in Section 7.2.3.3, due to equipment limitations, Vendor B's centerless profile grinding technique did not produce valves with the desired dimensional accuracy. Similarly, Vendor D's peel-grinding approach suffered from equipment limitations. The equipment was not properly set up for the longer Series 149 valves and, therefore, did not consistently meet the valve dimensional requirements.

Both of these techniques were, therefore, eliminated from the final machining campaign. Only the valves machined at Vendors A and C were found to meet the quality requirements and, hence, were included in the final durability tests and production demonstration activities.

The 8V-149 engine (1100 hp @ 1900 rpm) devoted to the testing was fitted with twenty four ceramic NT551 valves, all originating from Vendor A. The test to be completed on this engine consisted of 1000 hours of the mine-haul cycle.

The engine was started for a runin but, after a couple of hours, a turbo failure occurred. The apparent cause was debris in the exhaust manifold. The debris was removed, and the manifold cleaned. The turbocharger was replaced, and the engine was restarted. After completing 100 hours of testing, the exhaust-gas temperature reached 800°C; exceeding 850°C in parts of exhaust headers. The engine was shut down, and four ceramic valves in one cylinder were found to have failed. Three valves failed in the stem about two inches above the combustion face, and the fourth valve had the edge of the head chipped off. The ceramic pieces in the exhaust manifold, as well as in the turbine housing, were collected for the failure analysis to be performed by the DDC Materials Department and by NRDC. The purpose of this analysis was to define the type of loading that caused the fracture.

The engine layout is shown below in Figure 57:

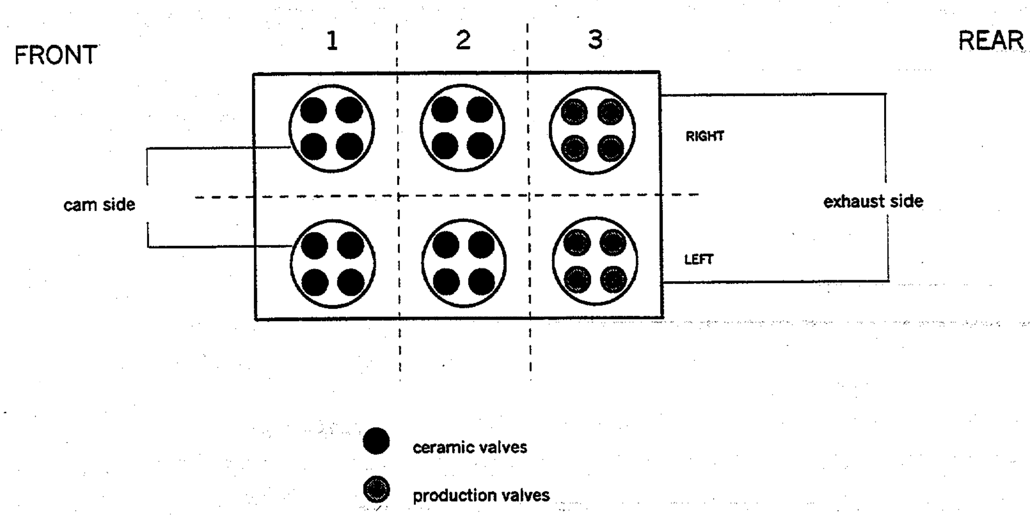


Figure 57. 8V Series 149 Engine Layout

Thorough analyses of the failed valves showed no material-related defects. It was tentatively surmised that the failure might have occurred due to valve misalignment during installation and/or subsequent durability testing. Consequently, the engine was reassembled and testing resumed. Production metal valves were installed in place of broken ceramic valves since no more ceramic valves were available.

At 250 hours of testing, a borescope inspection of the cylinders with ceramic valves was performed. All ceramic valves appeared to be in good shape. Testing resumed after inspection. Five hundred hours of durability testing was completed without any adverse incidents.

The viability of the two cost-effective machining procedures, discussed in Section 7.2.3.3 was evaluated by performing additional engine-durability tests employing the mine-haul cycle.

After a few early failures (infant mortality), attributed to relatively rough surface finish on the valve head (verified by subsequent fractography of the failed valves), the remaining 16 valves successfully completed the required 1000 hours of durability testing using the mine-haul cycle. Based upon these tests, the surface-finish specification on the valve-head region was modified with the concurrence of DDC. The same surface finish was subsequently required from the two machining vendors for the production-demonstration valves.

Seventeen valves machined by Vendor C were supplied to DDC for engine-durability testing following metrology and proof testing at NAC. These valves met the newly defined surface-finish specifications described above. DDC continued the rig testing with 16 Vendor A and 16 Vendor C valves to accumulate additional hours, and to evaluate various seat materials. Based upon the results of this testing effort, the valve subassembly design features (e.g. seat materials) were further optimized.

Eighty seven fully inspected and proof tested Series 149 NT551 silicon nitride valves were supplied to Detroit Diesel Corporation (DDC) for an additional 1000 hours of engine-durability testing. This test incorporated optimized cost-effective valve machining procedures and assembly design.

After 150 hours of testing (mine-haul cycle), failure was experienced in one of the 8 cylinders. Initial examination suggested failure of one valve followed by the other three (four valves/cylinder) due to subsequent impact damage.

7.3.3 Postmortem Analysis

The 4 broken and 28 intact valves were returned to NRDC by DDC for further analysis. Detailed failure analysis revealed the following:

- No obvious internal flaws (pore, inclusion, etc.) were detected on any of the fracture surfaces.
- No evidence of fatigue slow crack growth was observed.
- No obvious machining damage was in evidence near the remaining fracture origin (the fracture origin itself was lost in the debris).

- Discontinuous wear marks were observed on the valve seat; suggesting improper, non-uniform seating of the valve on the seat. Under extreme conditions, this could generate extremely high localized (Hertzian) stresses.
- The failure origin was tentatively identified near the seat/head radius interface (Figure 58) due to contact damage caused either by non-uniform seating and/or debris.
- All 28 unbroken valves from the other cylinder were examined by Liquid Dye Penetrant (LDP) to detect any signs of crack initiation from the seat/head radius interface due to fatigue. None of the 28 valves examined showed any evidence of surface cracking.

This concluded the durability testing of NT551 silicon nitride valves in Series 149 diesel engines with mine-haul cycle. Thus 1000 hours of durability testing was successfully demonstrated on NT551 valves. However, in order to assess the fatigue life of the silicon nitride valves, a decision was made in concurrence with the technical monitor of this program to determine the residual strength of the engine-tested valves. Engine tested valves were supplied to Oak Ridge National Laboratory to perform hydraulic pressure tests and to compare the burst pressure with those of the untested valves. The results of these evaluations are summarized below.

The fully machined valves from Vendors A and C were tested to failure before and after the engine-durability testing in order to assess the fatigue damage (if any) caused by the cyclic loading and/or the thermal environment of the engine.

As mentioned earlier, the Vendor A valves were CNC ground between centers and, hence, exhibited transverse grinding marks on the stem and the valve seat radius. On the contrary, Vendor C valves were subjected to compound centerless grinding in such a way that the grinding marks were almost parallel to the valve stem axis and, consequently, were called longitudinally machined valves. These valves were tested under hydraulic pressure on the head, simulating the diesel engine

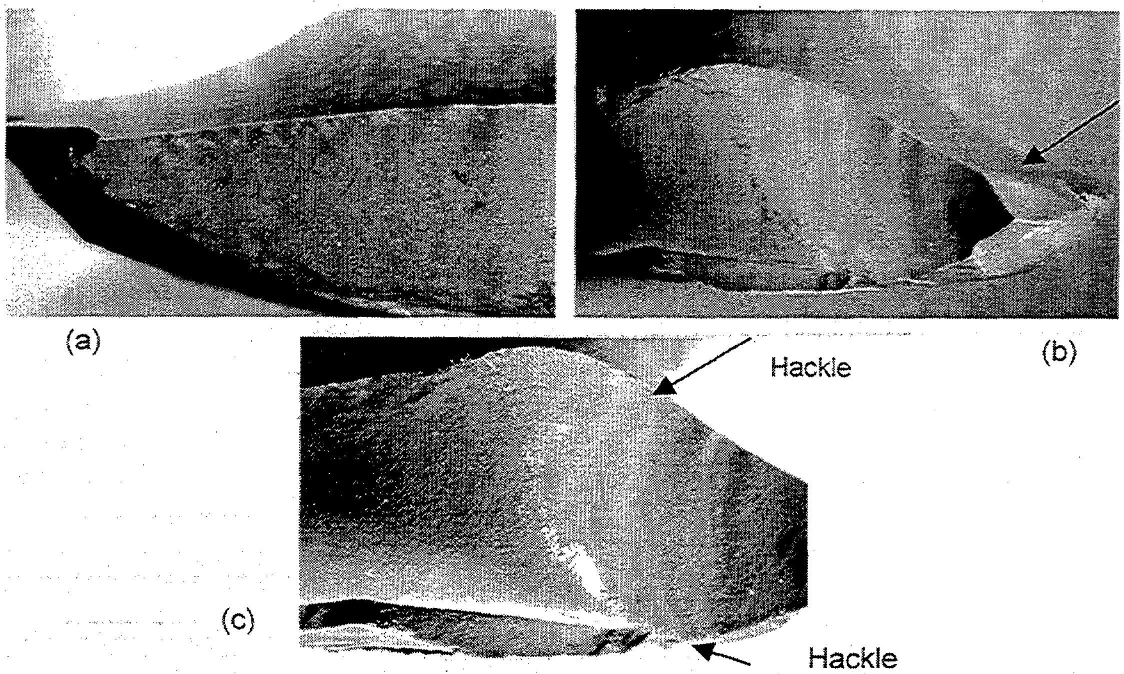
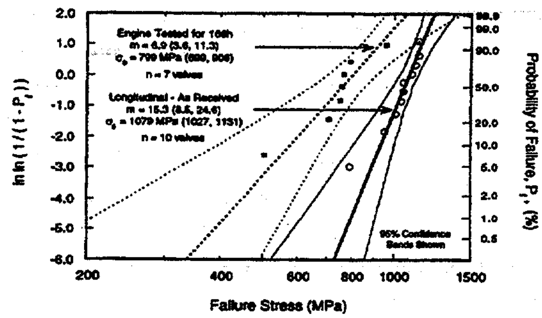


Figure 58. Fractography of Tested Valves

Figure 58. Fracture surface of Valve 1C from Cylinder 3L. Primary Wallner lines in (a) and (b) indicate crack propagation from left-to-right. Origin appears to be missing, but was probably located on upper surface of valve head near seat/head contact area [see arrow in (b)]. Some shear or twist hackle is also visible in (c) at upper middle of picture. Hackles are also present at arrow in (b), though not visible in the photograph, which also point back to the suspected origin. The discolored streaks visible in (b) and (c) appear to be a transfer film from rubbing contact with metal.

pressure environment (no thermal load). During the test, valves were seated on the actual valve seat used in durability tests. The failure pressure loads were noted and were subsequently utilized to compute the maximum stress in the head area. The failure stresses for the two types of valves (longitudinal and transverse) before and after durability testing are shown in the Weibull plots of Figure 59 and Figure 60, respectively. As is obvious from these figures, longitudinally machined valves suffer a higher loss in strength after the durability tests. However, the retained strengths in both cases are still significantly higher than the 160 MPa stress experienced by the valves in the diesel engine. After 1000 hours of durability testing, the average retained strengths of transversely and longitudinally machined valves are 636 MPa and 799 MPa, respectively.

The Strength of Longitudinally Machined Valves Reduced by Approximately 25% After 166 h of Engine Testing



Uncensored Data Shown

html/ornl

Figure 59. Weibull Plot of Longitudinally Machined Valves

The Strength and Weibull Modulus of Transversely Machined Valves Were Lower After 1000 h of Engine Testing

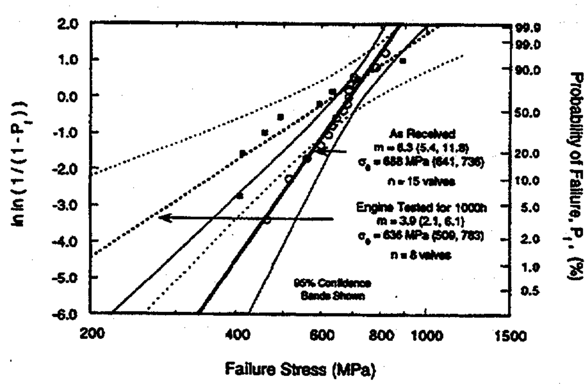


Figure 60. Weibull Plot of Transversely Machined Valves

All improved-process NT551 valves machined by Vendors A and C fully met DDC's material and proof-testing specifications. These valves also successfully completed 1000 hours of engine durability testing. However, NT551 valves experienced a higher incidence of infant mortality than NT451. DDC has speculated that the failures may have been caused by machining damage; particularly in the case of the valves ground by Vendor A utilizing an aggressive, cost-effective machining procedure. Vendor C utilized a relatively less aggressive machining procedure and judiciously oriented the machining marks parallel to the valve pull direction (preferred orientation). Therefore, it is believed that Vendor C's technique yielded a superior valve, which may be corroborated by the fact that Vendor C valves exhibited significantly higher retained strength than Vendor A valves after engine durability testing (Figure 59). In fact, the retained strengths of both the Vendor A and C valves well exceeded the operating total stresses in the engine. In light of these facts, machining-induced failure seems to be less probable. Two other potential causes for failure have been identified. One is incomplete contact between the valve head and the seat that produced higher contact stress, which was invariably observed on all engine-tested valves. In earlier testing, the valve-seat material was also found to have a very significant effect on the contact stresses and the life of the valves. The third identified potential cause for valve failure is long-term fatigue damage resulting from the high temperatures of the diesel engine environment. Additional work is required to determine the precise cause of the failures, and further study of fatigue damage may shed light on this aspect of failure analysis.

7.4 PROCESS DEMONSTRATION - TASK 4

7.4.1 Pre-Production - Task 4a

Under this subtask, a total of 200 preliminary design SiAlON (NT451) valves was fabricated; 100 with a 30° seat angle, and 100 with a 45° seat angle. All of these valves were inspected and delivered as follows in fulfillment of Milestone No. 2.

- 160 to DDC (80 with a 30° seat angle, and 80 with a 45° seat angle).
- 40 to ORNL (22 with a 30° seat angle, and 18 with a 45° seat angle).

All of these valves were processed through axial-pull proof testing with a load of 3000 lbs.

Control charts for the mechanical properties characteristics called out in DDC specification 15T-4/S149 developed under Preliminary Design Task 1a are provided in Figure 61, Figure 62, Figure 63, and Figure 64. These characteristics include: MOR strength at 1% probability of failure (POF), Weibull Modulus, fracture toughness, and hardness. Fracture toughness was the only parameter that did not consistently exceed DDC's specification. Incorporating NT551 silicon nitride into the program, as reported previously, rectified this deficiency of NT451.

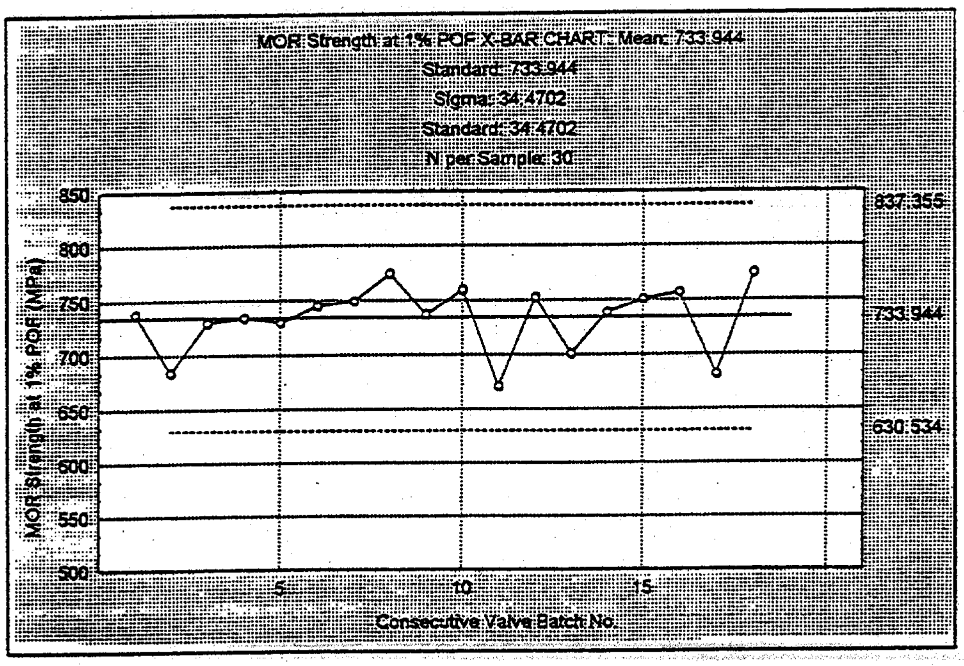


Figure 61. Control Chart for MOR Strength 1% POF

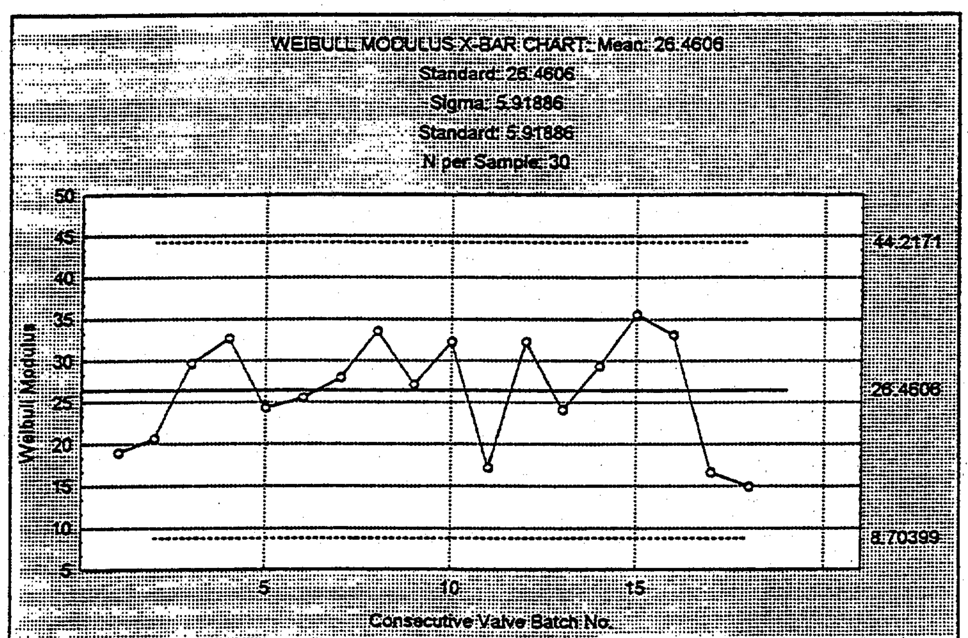


Figure 62. Control Chart for Weibull Modulus

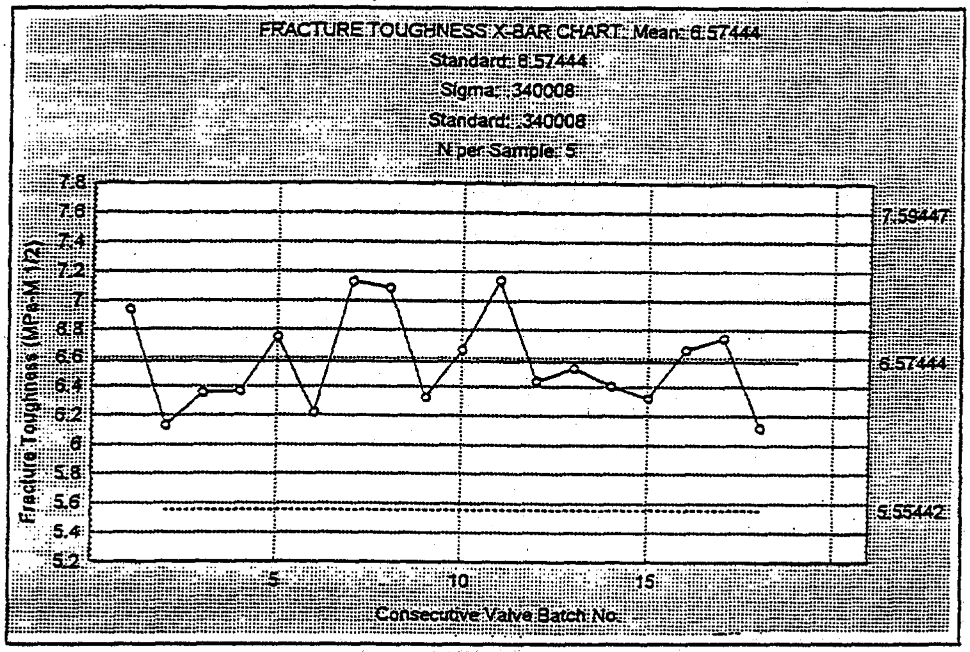


Figure 63. Control Chart for Fracture Toughness

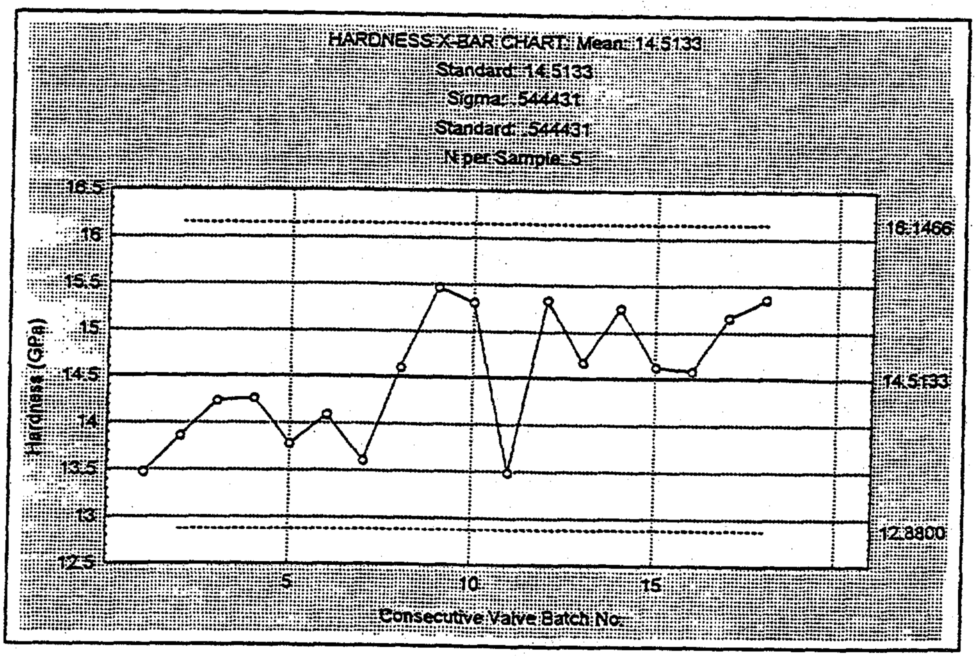


Figure 64. Control Chart for Hardness

NAC completed an analysis of the manufacturing data for these pre-production valves to determine: the current actual process capability for each critical component attribute, the actual process yields by process step, and the actual variable costs by process step. These data were used to: establish absolute goals for the Task 4b production process demonstration, validate the Process Cost Model developed by IBIS, and guide the production process development efforts.

7.4.2 Production - Task 4b

In fulfillment of the Milestone No. 6 requirement to fabricate 320 final design valves, 340 valves were finish machined at the three below vendor locations and inspected. The total machining times at Vendors A and C were documented in order to estimate the process improvement and the corresponding cost reduction.

The production demonstration set of NT551 valves was produced as follows:

Vendor A - 180 Valves (30 + 150)
Vendor C - 130 Valves (30 + 100)
Vendor D - 30 Valves

The specific machining procedure used by each of the three following vendors is discussed in detail in Section 7.2.3.3.

7.4.2.1 Vendor A - CNC Profile Grinding.

One hundred and fifty valves were finish-machined using the CNC profile grinding approach. Briefly, this technique involves high speed (>80 m/sec) rough grinding to remove approximately 93% of the stock, followed by finish machining using a superabrasive wheel. All 150 valves were fully inspected and proof tested in accordance with DDC specifications. Based on these measurements, process yield and reproducibility data were also established. The detailed dimensional and metrology data are included as Appendix C.

7.4.2.2 Vendor C - Centerless Grinding

One hundred fully finished valves were received from Vendor C. In accordance with DDC specifications, these valves also underwent full inspection and proof testing. Eighty seven fully qualified valves from this machining campaign were shipped to DDC to initiate an additional 1000 hours of engine durability testing. The detailed dimensional measurement and methodology data are included as Appendix C.

7.4.2.3 Vendor D - Peel Grinding

Thirty Series 149 diesel valves finished in accordance with DDC specifications were received from Vendor D. These valves were also inspected, proof tested, and delivered to DDC.

7.5 CONTINUOUS SINTERING PROCESS OPTIMIZATION FOR LOW-COST DIESEL VALVES - TASK 5

Sixteen silicon nitride valves were sintered in the continuous furnace, using four different fixturing procedures. The purpose of this test was to further improve the dimensional tolerance (stem bending) of the overall valve. The sintering parameters used were identical to those used in the previous Run #53.

Careful measurement of the stem bending TIR suggested no further improvement in dimensional control. Alternative fixturing approaches did not appear to be feasible in the current furnace due to its size limitations. In light of the lack of improvement in dimensional control, it was determined that additional experimentation to evaluate cost-reduction alternatives would not benefit the program. Consequently, no further work was performed under this task.

8. CONCLUSIONS

Advanced structural ceramics have demonstrated the properties, performance, and reliability that make them enabling materials for new, energy-efficient engine systems. High manufacturing cost is recognized as the last major barrier to the widespread use of these materials. Norton Advanced Ceramics (NAC) was selected to perform a major Advanced Ceramics Manufacturing Technology (ACMT) Program to design, develop, and demonstrate advanced manufacturing technology for the production of ceramic exhaust valves for diesel engines. The exhaust valve for the Detroit Diesel Corporation (DDC) Series 149 engine was chosen as the demonstration part for this program because it was considered an ideal component type to demonstrate cost-effective process improvements, it had near-term commercialization potential, and it would effectively demonstrate ceramic materials' performance advantages in a transportation engine system. NAC's NT551 silicon nitride was selected during the program to replace NAC's NT451 SiAlON because it offered the best opportunity for manufacturing cost reduction.

The NAC team met the overall program objectives: (1) to reduce the manufacturing cost by an order of magnitude, (2) to develop and demonstrate process capability and reproducibility, and (3) to validate ceramic valve performance, durability, and reliability in rig and engine testing. A cost-effective valve manufacturing process was fully established.

DDC defined the critical valve-design features based on finite element analysis and actual component testing. Design features evaluated and selected included valve-seat angle, keeper-groove geometry, and keeper-material hardness. The NT551 silicon nitride met DDC's material-specification requirements for material hardness, density, fracture toughness, MOR, Weibull modulus, porosity, and microstructure. No infant mortality was observed during testing, indicating effective component screening. Dynamic analysis of the valve-train system was conducted. Model refinements throughout the program enabled excellent agreement between predicted and measured valve-train characteristics.

Component manufacturing development, which included cost analysis, environmental safety and health assessments, process control, and intelligent processing, was performed by all program team members. In order to reduce the manufacturing cost of the silicon nitride valve, each unit operation of the valve manufacturing process was critically examined to improve reliability and to reduce overall cost. A Technical Cost Model (TCM) developed by IBIS, was used to evaluate the cost impact of changes in either production parameters or process design. It was concluded that the highest contributors to total cost were materials, grinding, and sintering. The model will continue to function as a repository for process information, and as a dynamic tool that will allow on-going analysis as input assumptions are updated and modified.

Together with NAC researchers at NRDC, BDM/MATSYS successfully developed and demonstrated an Intelligent Control System (ICS) for the spray drying of silicon nitride powder. Its implementation included: (a) hardware upgrades to improve process repeatability and uniformity; and (b) the development of a PC-based controller capable of operating the major components of the spray dryer, of monitoring, displaying, and recording process data, and of actively controlling the residual moisture content of the spray-dried powder. Control of the residual moisture ensures that the powder will have a uniform and consistent pressability. The integrated ICS for the spray-drying operation was subsequently transferred to the larger, production spray dryer at the NAC manufacturing plant, and was successfully brought on-line under this program. The valve dry bag isopressing operation was significantly improved to simultaneously reduce rejections and achieve green dimensions closer to net shape. The successful new design resulted in a 44% smaller fill volume, and reduced density and stress gradients within the pressed blank.

Batch sintered NT551 valves exhibited superior dimensional control as compared to the pre-production NT451 (SiAlON) valves. NT551 valves showed a factor of 3 reduction in valve bending (TIR), which directly reduces machining time. Continuous sintering was demonstrated as a viable process to reduce manufacturing cost. The continuous sintered properties of NT451 and NT551 were equal to or better than those measured for the same material formulations sintered in a batch furnace. During the program, significant improvements in valve dimensional control were achieved by optimizing various continuous-sintering parameters for both valve materials. The total indicated runout (TIR) was reduced by over 50%; however, on average, the TIR was still approximately 2 times greater than for conventional batch sintering. While it is anticipated that further improvements in TIR could be realized by vertical orientation during sintering, due to time and resource constraints, the batch sintering approach was selected for the valve production trials. The IBIS cost model predicted that continuous sintering followed by HIPing offers the most favorable combination of cost and performance. The initial continuous sintering work showed great potential and further development is recommended.

Development of machining techniques during the ACMT program resulted in significantly exceeding the order-of-magnitude cost-reduction objectives for this operation. Four production-grinding techniques were considered and evaluated. However, only two, CNC Profile and Compound Center Grinding, were used in the process demonstration trials due to component quality requirements.

The Norton Company Higgins Grinding Technology Center (HGTC) simulated production-scale, through-feed centerless plunge grinding of ceramics and transferred the technology to Deco-Grand. Cost analysis by IBIS showed the centerless plunge technique to be the lowest-cost option for production volumes greater than 4000 parts per year. However, dimensional control in early trials was found to be less than desirable. Although improved control was expected with better machine tools, due to program time constraints, this approach was not pursued further.

Chand Kare's Compound Center Grinding, a modified centerless grinding approach somewhat similar to Deco-Grand's technique, was added later in the program and showed similar cost advantages. Moreover, in the Chand process, grinding marks on the valve-head radius were parallel to the stem axis. These marks were predicted to be more benign from a grinding-damage perspective.

HGTC developed a cost-effective CNC profile grinding technique on a Studer grinder capable of machining advanced ceramic exhaust valves. A significant reduction in the rough machining time was accomplished using a high-speed MSL (metal single layered) wheel. A satisfactory reduction in the finishing time was also realized by using a high-bond-strength, vitrified-bonded wheel. The tolerance and surface finish met DDC's requirements. The technology was successfully validated in prototype and production demonstrations. For volumes between 1000 and 4000 parts per year, this CNC profile-grinding approach had the lowest predicted cost. The IBIS cost model also confirmed that grinding wheels have an enormous impact on the machining operation cost. Further cost reduction using CNC profile grinding is expected by incorporating new grinding wheels.

NAC evaluated the Junker Peel Grinding technique, initially on 10 NT451 valves and, subsequently, on 30 NT551 valves. This grinding approach is somewhat similar to HGTC's CNC profile-grinding technique, and is somewhat comparable in cost. This technique gave the lowest predicted cost for production volumes of fewer than 1000 parts per year. There were unexpected valve tolerance problems in the 30-valve trial, and this technique was not pursued further in the ACMT program.

Testing at DDC consisted of preliminary/screening, overhead fixture, and durability testing on a V-8 Series 149 engine using a Mine Haul Cycle. Ceramic valves were shown to provide high thermal strength and improved thermal insulation compared to metal components, which translated into higher peak-firing pressure thresholds, as well as reduced heat rejection to the coolant system and an overall increase in engine thermal efficiency. The mass was reduced by nearly 60% with the lightweight ceramic valve. Reducing the overall inertia of the engine valve train increased the overspeed capability by 300 rpm (15% of the engine rated speed). In addition, the lighter-weight ceramic valves significantly reduced the rocker arm loads. DDC successfully demonstrated over 1000 hours in the Series 149 diesel-engine durability test using both the baseline NT451 SiAlON valves and the later improved-process NT551 silicon nitride valves.

However, there were some NT551 valve failures. The failed valves were ground with some of the new, improved-process, cost-effective machining techniques. It was speculated, but not conclusively determined, that machining marks on the surface may have reduced the high-temperature fatigue strength of the valves, leading to premature failures. The cause of these failures may also have been due to the rig-test design. Further work is needed to confirm and correct the cause, whether it be machining damage, material fatigue, engine design, or a combination thereof.

The systematic development of improvements in each unit operation of the valve manufacturing process was validated by the production of 320 fully finished engine-ready valves. These valves met the dimensional requirements and provided the data to establish a process capability index. Incorporating targeted process improvements and the learning curve model (scale up) achieved the program goal of an order-of-magnitude reduction in manufacturing cost at a production volume of only slightly more than 2000 valves per year. A projected factor of 25 cost reduction was established for the modest production volume of 40,000 valves per year. Without incorporation of the ACMT process improvements, the projected cost reduction for volume alone was only a factor of 5 at 40,000 parts per year.

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11. APPENDICES

A. Wittmer Consultants Continuous Sintering Trial Data

B. Vendor A (CNC Profile Grinding) Dimensional and Metrology Data of Machined Valves

C. Vendor C (Centerless Grinding) Dimensional and Metrology Data of Machined Valves

APPENDIX A

Wittmer Consultants
Continuous Sintering Trial Data

Table I. Continuous Sintering Results for Initial Sintering Trials

Comp.	Sintering Temperature (T) and Time (t)							
	T4				T5			
	t1		t3		t1		t3	
	% Target Density	Wt. Loss %	% Target Density	Wt. Loss %	% Target Density	Wt. Loss %	% Target Density	Wt. Loss %
SLX-15	99.3	0.3	99.9	0.7	99.6	0.4	99.8	0.8
SLX-17	96.5	0.9	97.9	0.9	96.2	0.4	98.3	1.0
SLX-19	98.5	0.4	99.3	0.8	98.6	0.4	99.3	1.0

Table II. Continuous Sintering Results For Cylindrical Specimens

Comp.	Sintering Temperature (T) and Time (t)					
	T4					
	t1		t2		t3	
	% Target Density	Wt. Loss %	% Target Density	Wt. Loss %	% Target Density	Wt. Loss %
SLX-15	99.4	0.9	99.7	1.2	99.6	2.0
SLX-17	95.1	1.2	---	---	96.7	2.1
SLX-18	97.0	1.2	---	---	97.8	2.1
SLX-19	98.6	1.2	98.7	1.3	99.0	1.8
SLX-23	97.5	1.5	97.0	1.7	96.0	2.3

Table II. Continuous Sintering Results for Cylindrical Specimens (Continued)

Comp.	Sintering Temperature (T) and Time (t)			
	T5			
	t1		t3	
	% Target Density	Wt. Loss %	% Target Density	Wt. Loss %
SLX-15	99.1	1.0	99.8	1.4
SLX-17	94.3	0.8	96.6	1.5
SLX-18	96.6	1.0	97.7	1.5
SLX-19	98.2	0.9	99.0	1.6
SLX-23	97.2	1.4	97.1	1.9

Table III. Continuous Sintering Results for Preliminary Lot of NT-551

Sintering Conditions		Immersion Density (g/cc)	Weight Loss (%)
Temp. Code	Time Code		
2	3	3.20	0.67
3	2	3.18	0.63
3	3	3.20	0.67
3	4	3.22	0.68
4	1	3.18	0.64
4	2	3.20	0.66
4	3	3.26	0.91
4	4	3.26	0.73
5	1	3.17	0.68
5	2	3.23	0.86
5	3	3.25	0.94
5	4	3.26	1.02

Table IV. Results of Continuous Sintering of NT-551 Billets and Valves

ID	Time/Temp.	Belt Speed	Wt. Loss (%)	% T. Density
Billets				
10	t4/T5	3	1.02-1.03	96.5
11	t4/T5	3	1.11-1.48	97.9
12	t4/T5	3	0.89-1.11	98.8
10	t3/T5	4	0.92-1.07	94.8
11	t3/T5	4	0.88-1.02	96.6
12	t3/T5	4	0.74-0.87	97.9
Valves				
10	t4/T5	3	1.00	93.9
11	t4/T5	3	1.22	95.4
12	t4/T5	3	0.95	96.6
10	t3/T5	4	0.92	92.3
12	t3/T5	4	0.81	95.4

Table V. Sintering Results for 4 NT-551 Formulation/Processing Conditions.

RUN NO. 51	TEMPERATURE & TIME 7/2		BELT SPEED 7	ZONE TEMPERATURES		
				7	7	7
ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
SM2-1-6	ALL OF THESE SAMPLES SHOWED SIGNIFICANT SILICON METAL FORMATION ON THE SURFACES AND/OR EDGES					
ND2-13-6						
ND2-15-1-N						
ND2-15-1-E						
ND2-16-T						
NT2-16-D						

Table VI. Sintering Results for 4 NT-551 Formulation/Processing Conditions.

RUN NO. 52	TEMPERATURE & TIME 6/4		BELT SPEED 7	ZONE TEMPERATURES		
				6	6	6
ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
SM2-1-1	77.47	76.89	0.7	52.77	3.19	97.2
ND2-13-1	74.73	74.09	0.9	50.82	3.18	97.4
ND2-15-1K	73.69	73.19	0.7	49.26	3.06	93.5
ND2-15-1M	73.32	72.93	0.5	49.07	3.06	93.5
ND2-16-H	78.13	77.73	0.5	52.96	3.14	95.9
ND2-16-R	78.11	77.89	0.3	53.04	3.14	95.9

Table VII. Sintering Results for 4 NT-551 Formulation/Processing Conditions.

RUN NO. 53	TEMPERATURE & TIME 5/4		BELT SPEED 4	ZONE TEMPERATURES		
				5	5	5
ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
SM2-1-2	78.35	77.61	0.9	53.48	3.22	98.1
SM2-1-3	77.08	76.34	1.0	52.73	3.23	98.6
ND2-13-2	74.73	73.95	1.0	50.96	3.22	98.4
ND2-13-3	75.31	74.45	1.1	51.30	3.22	98.3
ND2-15-1H	73.51	72.88	0.9	49.46	3.11	95.2
ND2-15-1C	73.26	72.59	0.9	49.26	3.11	95.1
ND2-16-B	78.05	77.54	0.7	53.26	3.19	97.6
ND2-16-Q	77.79	77.09	0.9	52.96	3.19	97.7

Table VIII. Sintering Results for 4 NT-551 Formulation/Processing Conditions.

RUN NO. 54	TEMPERATURE & TIME 5/2		BELT SPEED 7	ZONE TEMPERATURES		
				5	5	5
ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
SM2-1-4	79.26	78.47	1.0	53.10	3.09	94.3
SM2-1-5	78.77	78.01	1.0	53.51	3.18	97.1
ND2-13-4	74.52	73.93	0.8	50.35	3.14	95.9
ND2-13-5	75.09	74.51	0.8	50.66	3.12	95.5
ND2-15-1G	74.49	73.10	1.9	48.82	3.01	92.1
ND2-15-1D	74.16	72.61	2.1	48.42	3.00	91.8
ND2-16-C	79.63	77.93	2.1	52.68	3.09	94.4
ND2-16-N	79.57	77.70	2.4	52.59	3.09	94.6

Table IX. Sintering Results for 4 NT-551 Formulation/Processing Conditions.

RUN NO. 55	TEMPERATURE & TIME 6/4		BELT SPEED 6	ZONE TEMPERATURES		
				6	6	6
ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
SM2-1-7	---	76.60	---	53.14	3.26	99.8
SM2-1-8	---	77.29	---	53.66	3.27	100.0
ND2-13-7	---	74.54	---	51.56	3.24	99.2
ND2-13-8	---	73.06	---	50.55	3.25	99.3
ND2-15-1A	74.59	72.84	2.3	49.84	3.17	96.8
ND2-15-1B	74.42	72.65	2.4	49.85	3.19	97.4
ND2-16-P	79.37	77.17	2.8	53.44	3.25	99.4
ND2-16-S	79.69	77.40	2.9	53.30	3.21	98.2
ROD A1	59.91	58.72	2.0	39.98	3.13	95.8
ROD ND2-10	60.77	58.69	3.4	39.95	3.13	95.8

Table X. Sintering Results for ND2-22/NT-551.

RUN NO. 62	TEMPERATURE & TIME 5/4		BELT SPEED 4	ZONE TEMPERATURES		
				5	5	5
ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
ND2-22-1	78.07	77.62	0.6	53.75	3.25	99.2
ND2-22-5	77.57	77.18	0.5	53.55	3.27	99.6
ND2-22-13	77.52	77.10	0.5	53.50	3.27	99.6
ND2-22-4	77.53	76.88	0.8	53.19	3.25	99.0
ND2-22-6	77.75	77.03	0.9	53.32	3.25	99.1
ND2-22-14	77.52	76.77	1.0	53.26	3.27	99.6
ND2-22-41	77.44	76.77	0.9	53.16	3.25	99.1
ND2-22-21	77.54	76.85	0.9	53.26	3.26	99.3
ND2-22-38	76.63	75.72	1.2	52.66	3.28	100.1
ND2-22-27	77.57	76.72	1.1	52.99	3.23	98.6
ND2-22-23	77.67	76.99	0.9	53.22	3.24	98.8
ND2-22-42	77.63	76.85	1.0	53.23	3.25	99.2

Table XI. Sintering Results for ND2-16/NT-551.

RUN NO. 62	TEMPERATURE & TIME 5/4		BELT SPEED 4	ZONE TEMPERATURES		
				5	5	5
ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
ND2-16-1	78.17	77.48	0.9	53.32	3.21	97.8
ND2-16-2	78.14	77.34	1.0	53.22	3.21	97.8
ND2-16-3	77.41	76.85	0.7	52.79	3.19	97.4
ND2-16-8	77.84	77.05	1.0	53.02	3.21	97.8
ND2-16-9	77.75	77.16	0.8	53.04	3.20	97.5
ND2-16-12	77.93	77.06	1.1	53.02	3.21	97.7
ND2-16-18	78.13	77.26	1.1	53.19	3.21	97.9
ND2-16-20	77.98	77.32	0.8	53.25	3.21	97.9
ND2-16-26	78.24	77.39	1.1	53.22	3.20	97.6
ND2-16-41	77.81	77.11	0.9	53.04	3.20	97.7
ND2-16-42	78.03	77.29	1.0	53.16	3.20	97.7
ND2-16-43	78.03	77.29	0.9	53.16	3.20	97.6

XII. Sintering Results for ND2-22/NT-551 Tiles.

RUN NO. 66	TEMPERATURE & TIME 4/4		BELT SPEED 4	ZONE TEMPERATURES		
				4	4	4
TILE ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
ND2-22-31	77.44	76.70	1.0	52.71	3.20	97.5
ND2-22-32	77.31	76.58	1.0	52.70	3.21	97.8
ND2-22-36	77.67	76.92	1.0	52.80	3.19	97.2
ND2-22-40	77.78	77.05	0.9	52.93	3.19	97.4
ND2-22-30	77.66	76.71	1.2	52.99	3.23	98.6
ND2-22-44	77.62	76.76	1.1	52.72	3.19	97.3
ND2-22-8	77.46	76.72	1.0	52.68	3.19	97.3
ND2-22-11	77.35	76.58	1.0	52.60	3.19	97.3
ND2-22-12	77.32	76.45	1.1	52.69	3.22	98.1
ND2-22-7	77.88	77.14	1.0	53.29	3.23	98.6
ND2-22-20	77.85	77.01	1.1	53.21	3.24	98.6
ND2-22-18	77.67	76.95	0.9	52.84	3.19	97.3

XIII. Sintering Results for ND2-16/NT-551 Tiles.

RUN NO. 66	TEMPERATURE & TIME 4/4		BELT SPEED 4	ZONE TEMPERATURES		
				4	4	4
TILE ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
ND2-16-30	77.99	77.29	0.9	52.75	3.15	96.0
ND2-16-33	77.99	77.29	0.9	52.91	3.17	96.7
ND2-16-16	78.23	77.47	1.0	52.92	3.16	96.2
ND2-16-5	78.23	77.63	0.8	53.09	3.16	96.4
ND2-16-35	78.19	77.53	0.8	52.98	3.16	96.3
ND2-16-32	78.05	77.46	0.8	52.98	3.16	96.5
ND2-16-38	78.18	77.40	1.0	52.93	3.16	96.4
ND2-16-39	78.33	77.63	0.9	53.15	3.17	96.7
ND2-16-36	78.12	77.44	0.9	53.08	3.18	96.9
ND2-16-29	78.16	77.56	0.8	52.99	3.16	96.3
X1	76.52	76.03	0.6	52.07	3.17	96.7
X2	76.48	76.07	0.5	52.05	3.17	96.6
X3	76.58	75.91	0.9	51.99	3.17	96.8

XIV. Sintering Results for ND2-16/NT-551 Valves.

RUN NO. 66	BELT SPEED 4	ZONE TEMPERATURES		
		4	4	4
VALVE ID	FIRED WT (g)	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
ND2-17-1	185.36	125.69	3.11	94.7
ND2-17-2	190.26	129.46	3.13	95.4
ND2-16-19H	110.01	74.13	3.07	93.5
ND2-16-18T	113.82	76.60	3.06	93.2
ND2-16-20H	113.83	76.85	3.08	93.8
ND2-16-17T	114.42	76.94	3.05	93.1
ND2-16-21H	114.38	77.25	3.08	93.9
ND2-16-8T**	114.43	77.08	3.06	93.4
ND2-16-22H	114.29	77.01	3.07	93.5
ND2-16-9T	119.91	80.41	3.04	92.5
ND2-21-21H	116.01	79.28	3.16	96.3
ND2-21-22T	113.98	77.87	3.16	96.3
ND2-21-20H	116.66	79.61	3.15	96.0
ND2-21-9T	120.87	82.61	3.16	96.3
ND2-21-18H	115.77	79.20	3.17	96.5
ND2-21-10T	122.34	83.67	3.16	96.4

Table XV. Sintering Results for ND2-24 and ND2-25/NT-551 Pellets.

RUN NO.80	TEMPERATURE & TIME 5/4		BELT SPEED 4	ZONE TEMPERATURES		
				5	5	5
PELLET ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
ND2-24-1B	11.72	11.58	1.2	8.04	3.27	99.8
ND2-24-2B	11.81	11.69	1.0	8.12	3.27	99.7
ND2-25-1B	11.72	11.58	1.2	8.04	3.27	99.7
ND2-25-2B	11.66	11.52	1.2	8.00	3.27	99.8

Table XVI. Sintering Results for ND2-24 and ND2-25/NT-551 Rods.

RUN NO. 80	TEMPERATURE & TIME 5/4		BELT SPEED 4	ZONE TEMPERATURES		
				5	5	5
ROD ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
ND2-24-1R	26.52	26.24	1.0	18.13	3.23	98.8
ND2-24-2R	26.53	26.24	1.1	18.14	3.24	98.9
ND2-24-3R	27.01	26.73	1.0	18.45	3.23	98.6
ND2-25-2R	26.92	26.66	1.0	18.42	3.24	98.8
ND2-25-3R	26.17	25.88	1.1	17.88	3.24	98.8
ND2-25-4R	26.09	25.81	1.1	17.82	3.23	98.6
ND2-24-4R	25.51	25.24	1.1	17.44	3.24	98.8
ND2-25-1R	26.63	26.35	1.1	18.19	3.23	98.6

Table XVII. Sintering Results for ND2-25 and ND2-24/NT-551 Tiles.

RUN NO. 80	TEMPERATURE & TIME 5/4		BELT SPEED 4	ZONE TEMPERATURES		
				5	5	5
TILE ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
ND2-25-5	78.89	77.90	1.3	53.99	3.26	99.5
ND2-25-6	78.70	78.02	0.9	54.04	3.25	99.4
ND2-25-7	78.68	77.87	1.0	53.97	3.26	99.5
ND2-25-1T	78.34	77.58	1.0	53.65	3.24	99.0
ND2-25-2T	73.66	72.96	1.0	50.42	3.24	98.8
ND2-25-3T	70.10	69.34	1.1	47.95	3.24	99.0
ND2-25-A-4T	78.67	77.82	1.1	53.88	3.25	99.2
ND2-24-1	78.16	77.14	1.3	53.47	3.26	99.5
ND2-24-2	78.37	77.50	1.1	53.71	3.26	99.5
ND2-24-3	78.20	77.44	1.0	53.65	3.25	99.4
ND2-24-1T	75.24	74.34	1.2	51.43	3.24	99.1
ND2-24-3T	73.03	72.38	0.9	50.05	3.24	99.0

XVIII. Sintering Results for Lot No. 7/NT-551 Valves.

RUN NO. 85	TEMPERATURE & TIME 6/6		BELT SPEED 6	ZONE TEMPERATURES		
				6	6	6
VALVE ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
7/6 (1)ST	116.9424	BROKEN TO OBSERVE CROSS SECTION				
7/10 (2)SH	116.5784	115.5163	0.91	77.3140	3.02	92.47
7/7 (3)TB	116.4312	115.3951	0.89	78.0006	3.09	94.37
7/2 (4)HT	116.9853	115.7406	1.06	78.8530	3.14	95.95
7/9 (5)HB	116.7482	115.4084	1.15	78.6460	3.14	96.00
7/3 (6)TT	117.4495	116.1061	1.14	78.986	3.13	95.65

XIX. Sintering Results for Lot No. 7/NT-551 Valves.

RUN NO. 86	TEMPERATURE & TIME 6/4		BELT SPEED 4	ZONE TEMPERATURES		
				6	6	6
VALVE ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
7/8 (7)ST	116.4993	115.4154	0.93	79.5305	3.22	98.36
7/4 (8)TT	116.9197	115.1289	1.53	79.2433	3.21	98.11
7/5 (9)HB	116.4297	115.1800	1.07	79.3380	3.21	98.27
7/1 (10)SH	116.3349	114.6375	1.46	79.2236	3.24	98.99

Table XX. Coded Data for "GOOD" Valves Run 8/28-9/24/96

RUN NO. 100	TEMPERATURE & TIME 5/4		BELT SPEED 4	ZONE TEMPERATURES		
				5	5	5
VALVE ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
1 (7-16)	116.917	115.760	0.99	79.664	3.21	98.07
2 (7-11)	116.685	115.416	1.09	79.408	3.21	98.02
3 (7-17)	116.527	115.364	1.00	79.311	3.20	97.85
4 (7-21)	116.926	115.576	1.15	79.523	3.21	98.03
7 (7-23)	116.797	115.389	1.21	79.519	3.22	98.38
9 (7-14)	116.732	115.622	0.95	79.671	3.22	98.35
10 (7-26)	117.141	115.920	1.04	79.843	3.21	98.26
11 (7-24)	116.384	114.919	1.26	79.144	3.21	98.23
12 (7-20)	116.465	115.001	1.26	79.201	3.21	98.24
13 (7-22)	116.498	115.492	0.86	79.466	3.21	98.04
15 (7-27)	116.738	115.796	0.81	79.844	3.22	98.50
17 (7-30)	116.924	115.585	1.15	79.692	3.22	98.48
18 (7-15)	113.545	112.516	0.91	77.682	3.23	98.78
22 (7-2)	117.003	115.771	1.05	79.812	3.22	98.46
28 (7-10)	117.102	115.946	0.99	80.106	3.24	98.93

Table XXI. Coded Data for "BAD" Valves Run 9/24-9/28/96

RUN NO. 100	TEMPERATURE & TIME 5/4		BELT SPEED 4	ZONE TEMPERATURES		
				5	5	5
VALVE ID	DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
5 (7-28)	117.112	115.792	1.13	79.658	3.20	98.00
6 (7-1)	116.969	115.660	1.12	79.741	3.22	98.47
8 (7-4)	116.680	115.282	1.20	79.379	3.21	98.19
14 (7-25)	116.476	115.196	1.10	79.349	3.21	98.27
16 (7-29)	116.991	115.786	1.03	79.719	3.21	98.17
19 (7-5)	115.711	114.229	1.28	78.798	3.22	98.59
20 (7-7)	116.931	115.767	1.00	79.699	3.21	98.16
21 (7-9)	115.578	114.402	1.02	78.787	3.21	98.23
22 (7-2)	117.003	115.771	1.05	79.812	3.22	98.46
24 (7-13)	115.765	114.427	1.16	78.931	3.22	98.58
25 (7-3)	116.489	115.286	1.03	79.572	3.23	98.72
26 (7-6)	116.688	115.476	1.04	79.541	3.21	98.27
27 (7-8)	117.062	115.244	1.55	79.478	3.22	98.54
(7-12)	BROKE DURING SHIPPING					
(7-18)	BROKE DURING SHIPPING					

Table XXII. Comments on Cracked or Broken "BAD" Valves

RUN NO. 100	TEMPERATURE & TIME 5/4	BELT SPEED 4	ZONE TEMPERATURES 5
VALVE ID	COMMENTS ON AS-RECEIVED VALVES	COMMENTS ON SINTERED VALVES	
5 (7-28)	CHIP ON TOP	CRACK IN HEAD AT 9:00	
6 (7-1)	NO DEFECTS NOTICED	CRACK IN HEAD AT 4:00	
8 (7-4)	NO DEFECTS NOTICED	CRACK IN HEAD AT 5:00	
14 (7-25)	NO DEFECTS NOTICED	CRACK IN HEAD AT 12:00	
16 (7-29)	NO DEFECTS NOTICED	CRACK IN HEAD AT 7:00	
19 (7-5)	TOP CHIPPED	CRACK IN HEAD AT 2:00	
20 (7-7)	NO DEFECTS NOTICED	CRACK IN HEAD AT 5:00	
21 (7-9)	TOP CHIPPED	CRACK IN HEAD AT 12:00	
22 (7-2)	NO DEFECTS NOTICED	CRACK IN HEAD AT 6:00	
24 (7-13)	HEAD CHIPPED	NO ADDITIONAL DAMAGE	
25 (7-3)	NO DEFECTS NOTICED	CRACK IN HEAD AT 11:00	
26 (7-6)	NO DEFECTS NOTICED	CRACK IN HEAD AT 11:00	
27 (7-8)	HEAD CHIPPED ON EDGE	CRACK IN HEAD AT 6:00	
(7-12)	BROKE DURING SHIPPING		
(7-18)	BROKE DURING SHIPPING		

Table XXIII. Continuous Sintering Results

RUN NO. 105		TEMPERATURE & TIME 5/4 Belt Speed 4			ZONE TEMPERATURES		
					5	5	5
ID		DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
Boat	Lot 17						
1	1	117.64	116.29	1.1	80.20	3.22	98.4
2	2	116.98	115.44	1.3	79.59	3.22	98.3
3	3	117.19	115.95	1.1	79.85	3.21	98.1
4	4	117.04	115.51	1.3	79.61	3.22	98.2
5	5	115.57	114.41	1.0	79.03	3.23	98.7
6	6	117.20	116.01	1.0	79.85	3.21	98.0
7	7	117.22	116.37	0.7	80.25	3.22	98.4
8	8	117.17	116.37	0.7	80.23	3.22	98.3
9	9	117.20	116.16	0.9	80.14	3.22	98.5
10	10	117.42	116.42	0.9	80.30	3.22	98.4
11	31	105.65	104.50	1.1	71.94	3.21	98.0
12	32	102.83	102.32	0.5	70.59	3.22	98.5
1	33	106.82	105.95	0.8	73.09	3.22	98.4
2	34	106.73	105.43	1.2	72.65	3.22	98.2
3	36	102.50	101.11	1.4	69.80	3.23	98.6

Table XXIV. Continuous Sintering Results

RUN NO. 105		TEMPERATURE & TIME 5/4 Belt Speed 4			ZONE TEMPERATURES		
					5	5	5
ID		DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
Boat	Lot 17						
4	38	106.90	105.82	1.0	72.95	3.22	98.3
5	40	103.41	101.65	1.7	70.09	3.22	98.3
6	51	118.24	117.28	0.8	80.89	3.22	98.4
7	52	118.15	117.23	0.8	80.80	3.22	98.3
8	53	116.98	116.07	0.8	80.04	3.22	98.4
9	54	116.86	115.86	0.9	79.93	3.22	98.5
10	55	118.47	117.47	0.8	81.13	3.23	98.7
11	56	116.83	116.00	0.7	79.98	3.22	98.3
12	57	116.91	115.83	0.9	79.87	3.22	98.3
1	58	116.95	116.15	0.7	80.03	3.22	98.2
2	59	117.18	116.23	0.8	80.11	3.22	98.3
3	60	117.22	116.19	0.9	80.14	3.22	98.4
4	61	117.29	116.31	0.8	80.24	3.22	98.5
5	62	117.31	116.39	0.8	80.18	3.21	98.2
6	63	117.30	116.43	0.7	80.17	3.21	98.0
7	64	117.39	116.47	0.8	80.27	3.22	98.2
8	65	117.44	116.27	1.0	80.27	3.23	98.6

Table XXVI. Continuous Sintering Results

RUN NO. 105		TEMPERATURE & TIME 5/4			ZONE TEMPERATURES		
					5	5	5
ID		DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
Boat	Lot 18						
11	80	117.47	116.47	0.9	80.44	3.23	98.7
12	81	117.20	116.12	0.9	80.22	3.23	98.8
1	82	116.96	115.93	0.9	80.13	3.24	98.9
2	83	116.84	115.95	0.8	80.05	3.23	98.6
3	84	117.28	116.32	0.8	80.31	3.23	98.6
4	85	117.19	116.27	0.8	80.24	3.23	98.5
5	86	117.24	116.22	0.9	80.23	3.23	98.6
6	87	116.99	115.94	0.9	80.08	3.23	98.7
7	88	116.98	116.02	0.8	80.11	3.23	98.6
8	89	115.92	114.72	1.0	79.25	3.23	98.7
9	90C	116.39	115.46	0.8	79.67	3.23	98.5
10	92	116.35	115.54	0.7	79.59	3.21	98.1
11	93	116.42	115.41	0.9	79.68	3.23	98.6
12	94	116.47	115.30	1.0	79.52	3.22	98.4
1	95	116.22	115.14	0.9	79.42	3.22	98.4
2	96	116.41	115.37	0.9	79.58	3.22	98.4
3	97	116.72	115.77	0.8	79.88	3.23	98.5
4	98	116.66	115.81	0.7	79.92	3.23	98.5
5	99	116.60	115.53	0.9	79.75	3.23	98.6
6	100	118.14	117.22	0.8	81.00	3.24	98.8

Table XXV. Continuous Sintering Results

RUN NO. 105		TEMPERATURE & TIME 5/4 Belt Speed 4			ZONE TEMPERATURES		
					5	5	5
ID		DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
Boat	Lot 17						
9	66	117.26	116.42	0.7	80.16	3.21	98.0
10	67	117.20	116.23	0.8	80.13	3.22	98.3
11	68C	117.30	116.53	0.7	80.20	3.21	97.9
12	69	117.21	116.39	0.7	80.19	3.22	98.2
1	70	117.24	116.32	0.8	80.15	3.22	98.2
2	71	119.08	118.22	0.7	81.45	3.22	98.2
3	72	116.66	115.60	0.9	79.82	3.23	98.7
4	73C	117.38	116.39	0.8	80.19	3.22	98.2
5	74	117.01	116.07	0.8	80.09	3.23	98.5
6	75	117.02	115.97	0.9	80.08	3.23	98.7
7	76	117.12	115.93	1.0	80.09	3.23	98.8
8	77	117.24	116.26	0.8	80.22	3.23	98.5
9	78C	117.45	116.39	0.9	80.13	3.21	98.0
10	79	117.50	116.39	0.9	80.37	3.23	98.7

Table XXVI. Continuous Sintering Results

RUN NO. 105		TEMPERATURE & TIME 5/4			ZONE TEMPERATURES		
					5	5	5
ID		DRY WT (g)	FIRED WT (g)	WT LOSS %	SUSPENDED WT (g)	DENSITY (g/cc)	% TARGET DENSITY
Boat	Lot 18						
11	80	117.47	116.47	0.9	80.44	3.23	98.7
12	81	117.20	116.12	0.9	80.22	3.23	98.8
1	82	116.96	115.93	0.9	80.13	3.24	98.9
2	83	116.84	115.95	0.8	80.05	3.23	98.6
3	84	117.28	116.32	0.8	80.31	3.23	98.6
4	85	117.19	116.27	0.8	80.24	3.23	98.5
5	86	117.24	116.22	0.9	80.23	3.23	98.6
6	87	116.99	115.94	0.9	80.08	3.23	98.7
7	88	116.98	116.02	0.8	80.11	3.23	98.6
8	89	115.92	114.72	1.0	79.25	3.23	98.7
9	90C	116.39	115.46	0.8	79.67	3.23	98.5
10	92	116.35	115.54	0.7	79.59	3.21	98.1
11	93	116.42	115.41	0.9	79.68	3.23	98.6
12	94	116.47	115.30	1.0	79.52	3.22	98.4
1	95	116.22	115.14	0.9	79.42	3.22	98.4
2	96	116.41	115.37	0.9	79.58	3.22	98.4
3	97	116.72	115.77	0.8	79.88	3.23	98.5
4	98	116.66	115.81	0.7	79.92	3.23	98.5
5	99	116.60	115.53	0.9	79.75	3.23	98.6
6	100	118.14	117.22	0.8	81.00	3.24	98.8

APPENDIX B

Vendor A (CNC Profile Grinding)
Dimensional and Metrology Data of Machined Valves

ACMT VALVE INSPECTION REPORT

		STEM				SEAT			VALVE HEAD			
Quantity	Valve #	Stem Dim. .3400/.3392	Stem Ra 8uin	Seat Ra 8uin	Stem Straightness 0.0004	Seat Runout .002 A	Large Radius R.75 +\-.02	Seat Angle 60 +/-15	Head Diameter 1.803/1.793	Head Runout 0.01	Corner Radii .025/.040	Location from Datum .147/.138
1	19-44	0.3396	5	4	0.00010	0.0008	good	good	1.7982	0.0007	good	good
2	19-46	0.3395	5	4	0.00010	0.0015	good	good	1.7978	0.0006	good	good
3	19-42	0.3400	8	5	0.00040	0.0011	good	good	1.7980	0.007	good	good
4	19-47	0.3397	6	7	0.00020	0.0004	good	good	1.7994	0.0012	good	good
5	19-48	0.3399	4	7	0.00015	0.0007	good	good	1.7973	0.0003	good	good
6	19-53	0.3396	5	5	0.00015	0.0009	good	good	1.7980	0.0024	good	good
7	19-56	0.3396	4	8	0.00020	0.001	good	good	1.7991	0.0075	good	good
8	19-58	0.3397	4	4	0.00010	0.0014	good	good	1.7990	0.0014	good	good
9	19-59	0.3399	4	4	0.00005	0.0008	good	good	1.7990	0.0065	good	good
10	19-60	0.34	5	5	0.00015	0.0003	good	good	1.7989	0.0075	good	good
11	20-1	0.3398	5	5	0.00005	0.0009	good	good	1.7976	0.0062	good	good
12	20-2	0.3398	4	5	0.00020	0.0014	good	good	1.7980	0.001	good	good
13	20-3	0.3399	5	4	0.00020	0.0013	good	good	1.7985	0.0015	good	good
14	20-4	0.3397	4	3	0.00005	0.0017	good	good	1.7987	0.0076	good	good
15	20-5	0.3396	4	3	0.00010	0.0014	good	good	1.7984	0.0024	good	good
16	20-6	0.3397	3	3	0.00010	0.0013	good	good	1.7992	0.0015	good	good
17	20-7	0.3398	4	3	0.00010	0.0008	good	good	1.7982	0.001	good	good
18	20-8	0.3398	3	3	0.00020	0.0011	good	good	1.7983	0.0058	good	good
19	20-9	0.3397	3	3	0.00010	0.0004	good	good	1.7974	0.0073	good	good
20	20-10	0.3397	3	2	0.00010	0.0004	good	good	1.7998	0.0044	good	good
21	20-11	0.3398	4	3	0.00030	0.0006	good	good	1.7992	0.0024	good	good
22	20-12	0.3395	4	3	0.00003	0.0005	good	good	1.7994	0.007	good	good
23	20-14	0.3395	4	3	0.00015	0.0008	good	good	1.7998	0.0021	good	good
24	20-15	0.3395	4	3	0.00010	0.0013	good	good	1.7987	0.0047	good	good
25	20-16	0.3396	6	3	0.00020	0.0020	good	good	1.7987	0.0019	good	good
26	20-17	0.3394	7	5	0.00025	0.0005	good	good	1.8007	0.0002	good	good
27	20-18	0.3395	7	4	0.0004	0.0008	good	good	1.7998	0.0006	good	good
28	20-20	0.3395	5	4	0.00007	0.0005	good	good	1.7992	0.0069	good	good
29	20-41	0.3396	3	4	0.00005	0.0005	good	good	1.8030	0.0035	good	good
30	20-42	0.3395	5	4	0.00015	0.0017	good	good	1.7986	0.0065	good	good
31	20-44	0.3394	6	5	0.00020	0.0016	good	good	1.7990	0.0048	good	good
32	20-45	0.3396	5	5	0.00005	0.0011	good	good	1.7989	0.0021	good	good

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		STEM				SEAT			VALVE HEAD			
Quantity	**Valve #**	**Stem Dim.** .3400/.3392	**Stem Ra** 8uin	**Seat Ra** 8uin	**Stem Straightness** 0.0004	**Seat Runout** .002 A	**Large Radius** R.75 +\-.02	**Seat Angle** 60 +/-15	**Head Diameter** 1.803/1.793	**Head Runout** 0.01	**Corner Radii** .025/.040	**Location from Datum** .147/.138
33	20-46	0.3397	5	2	0.00005	0.0013	good	good	1.7987	0.0012	good	good
34	20-47	0.3398	4	2	0.00005	0.0012	good	good	1.7990	0.0058	good	good
35	20-49	0.3396	3	4	0.00010	0.0009	good	good	1.8034	0.0031	good	good
36	20-52	0.3394	6	5	0.0004	0.002	good	good	1.8000	0.0028	good	good
37	20-58	0.3394	4	4	0.00007	0.0009	good	good	1.7982	0.0064	good	good
38	20-59	0.3395	3	4	0.00005	0.0017	good	good	1.7980	0.0008	good	good
39	20-60	0.3395	3	5	0.00020	0.0004	good	good	1.8034	0.002	good	good
40	20-62	0.3394	4	4	0.00010	0.0004	good	good	1.7980	0.001	good	good
41	20-70	0.3394	5	3	0.00025	0.0012	good	good	1.8028	0.0072	good	good
42	20-71	0.3396	3	7	0.00030	0.002	good	good	1.7981	0.0007	good	good
43	22-10	0.3395	4	7	0.00020	0.0003	good	good	1.7978	0.0086	good	good
44	22-11	0.3398	4	4	0.00030	0.0016	good	good	1.7985	0.0074	good	good
45	22-12	0.3397	4	7	0.00005	0.0001	good	good	1.7989	0.0065	good	good
46	22-13	0.3396	4	6	0.00030	0.0016	good	good	1.7983	0.0026	good	good
47	22-15	0.3397	5	6	0.00020	0.0013	good	good	1.7982	0.0018	good	good
48	22-17	0.3397	4	5	0.00015	0.0007	good	good	1.7970	0.0043	good	good
49	22-19	0.3397	6	4	0.00020	0.0012	good	good	1.7978	0.0057	good	good
50	22-23	0.3396	5	3	0.00010	0.0008	good	good	1.7985	0.003	good	good
51	22-24	0.3398	6	4	0.00015	0.0008	good	good	1.7986	0.0068	good	good
52	22-25	0.3397	4	8	0.00035	0.002	good	good	1.7988	0.0043	good	good
53	22-26	0.3396	6	6	0.00010	0.0002	good	good	1.7974	0.0011	good	good
54	22-27	0.3398	6	6	0.00010	0.0014	good	good	1.7986	0.0026	good	good
55	22-29	0.3395	4	8	0.00040	0.0009	good	good	1.7987	0.0048	good	good
56	22-30	0.3398	3	4	0.00040	0.0008	good	good	1.7992	0.002	good	good
57	22-31	0.34	5	4	0.00020	0.0004	good	good	1.7993	0.0015	good	good
58	22-33	0.3399	4	4	0.00020	0.0004	good	good	1.7980	0.0071	good	good
59	22-34	0.3397	4	5	0.00010	0.0005	good	good	1.7976	0.0063	good	good
60	22-35	0.3396	4	7	0.00005	0.0008	good	good	1.7981	0.0012	good	good
61	22-36	0.3397	5	5	0.00015	0.0008	good	good	1.7982	0.0022	good	good
62	22-37	0.3395	6	5	0.00005	0.0011	good	good	1.7985	0.0072	good	good
63	22-38	0.3396	4	4	0.00005	0.0006	good	good	1.7979	0.0062	good	good
64	22-39	0.3395	4	4	0.00030	0.0011	good	good	1.7980	0.0018	good	good

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		STEM				SEAT			VALVE HEAD			
Quantity	Valve #	Stem Dim. .3400/.3392	Stem Ra 8uin	Seat Ra 8uin	Stem Straightness 0.0004	Seat Runout .002 A	Large Radius R.75 +\-.02	Seat Angle 60 +/-15	Head Diameter 1.803/1.793	Head Runout 0.01	Corner Radii .025/.040	Location from Datum .147/.138
65	22-41	0.3399	4	3	0.00040	0.0011	good	good	1.7981	0.0017	good	good
66	22-44	0.3394	4	3	0.00001	0.0012	good	good	1.7978	0.0017	good	good
67	22-45	0.3396	4	3	0.00020	0.0004	good	good	1.7983	0.0007	good	good
68	22-51	0.3396	4	4	0.00005	0.0013	good	good	1.7994	0.0015	good	good
69	22-54A	0.3397	5	6	0.00005	0.0008	good	good	1.7984	0.0011	good	good
70	22-54B	0.3396	5	6	0.00040	0.001	good	good	1.7976	0.0021	good	good
71	22-55	0.3397	5	4	0.00025	0.0002	good	good	1.7998	0.0017	good	good
72	22-56	0.3397	4	6	0.00015	0.0003	good	good	1.7975	0.0055	good	good
73	22-57	0.3395	4	5	0.00030	0.0017	good	good	1.7991	0.0018	good	good
74	22-59	0.3396	4	6	0.00020	0.0008	good	good	1.7988	0.006	good	good
75	22-60	0.3397	5	5	0.00020	0.0012	good	good	1.7984	0.0033	good	good
76	22-62	0.3398	4	8	0.00005	0.0005	good	good	1.7978	0.0014	good	good
77	22-63	0.3398	4	8	0.00015	0.0015	good	good	1.7977	0.0019	good	good
78	22-64	0.3397	6	6	0.00010	0.0006	good	good	1.7990	0.0011	good	good
79	22-65	0.3396	4	8	0.00020	0.0008	good	good	1.7975	0.0017	good	good
80	22-67	0.3397	4	5	0.00020	0.001	good	good	1.7980	0.0067	good	good
81	22-68	0.3399	5	7	0.00015	0.0012	good	good	1.7983	0.0003	good	good
82	22-69	0.3396	4	8	0.00020	0.0009	good	good	1.7981	0.0046	good	good
83	V1	0.3396	4	3	0.00010	0.0017	good	good	1.7979	0.0022	good	good
84	V2	0.3394	2	3	0.00002	0.0007	good	good	1.7986	0.0058	good	good
85	V2A	0.3394	2	3	0.00020	0.0004	good	good	1.7982	0.0016	good	good
86	V3	0.3396	3	3	0.00015	0.0007	good	good	1.7987	0.0062	good	good
87	V6	0.3395	4	5	0.00030	0.0012	good	good	1.7980	0.0064	good	good
88	V7a	0.3397	3	4	0.00030	0.0012	good	good	1.7978	0.0056	good	good
89	V7b	0.3399	3	3	0.00040	0.0020	good	good	1.7979	0.0055	good	good
90	V10	0.3399	3	3	0.00040	0.0018	good	good	1.7990	0.0008	good	good
91	V12	0.3397	5	5	0.00010	0.0008	good	good	1.7991	0.0053	good	good
92	V13	0.3398	4	3	0.00015	0.0008	good	good	1.7983	0.0019	good	good
93	V17	0.3399	4	3	0.00040	0.0008	good	good	1.7992	0.0067	good	good
94	V19	0.3394	5	4	0.00002	0.0013	good	good	1.7984	0.0002	good	good
95	V20	0.3395	6	8	0.00007	0.0009	good	good	1.7988	0.0065	good	good
96	V21	0.3394	4	4	0.00002	0.0006	good	good	1.7988	0.0022	good	good

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		STEM				SEAT			VALVE HEAD			
Quantity	Valve #	Stem Dim. .3400/.3392	Stem Ra 8uin	Seat Ra 8uin	Stem Straightness 0.0004	Seat Runout .002 A	Large Radius R.75 +\-.02	Seat Angle 60 +/-15	Head Diameter 1.803/1.793	Head Runout 0.01	Corner Radii .025/.040	Location from Datum .147/.138
97	V23	0.3399	4	2	0.00002	0.0004	good	good	1.7982	0.0015	good	good
98	V24	0.3399	4	2	0.00020	0.0020	good	good	1.7990	0.0056	good	good
99	V25	0.3394	4	3	0.00001	0.0008	good	good	1.7992	0.0018	good	good
100	V26	0.3399	4	3	0.00001	0.0005	good	good	1.7994	0.0052	good	good
101	V27	0.34	4	4	0.00003	0.0006	good	good	1.7989	0.002	good	good
102	V28	0.3398	4	4	0.00030	0.0010	good	good	1.7988	0.0073	good	good
103	V30	0.3398	4	3	0.00005	0.0011	good	good	1.7982	0.0075	good	good
104	V31	0.3396	4	4	0.00020	0.0014	good	good	1.7998	0.0019	good	good
105	V32	0.3397	4	4	0.00007	0.0001	good	good	1.8027	0.0045	good	good
106	V33	0.3395	4	4	0.00010	0.0006	good	good	1.7988	0.005	good	good
107	V34	0.3393	6	4	0.00030	0.0012	good	good	1.7990	0.0013	good	good
108	V35	0.3393	4	3	0.00010	0.0012	good	good	1.7986	0.0042	good	good
109	V37	0.3397	4	3	0.00015	0.0011	good	good	1.7980	0.0012	good	good
110	19-50	0.340	4	6	0.00040	0.002	good	good	1.7981	0.0041	good	good
111	19-54	0.3398	5	4	0.00015	0.0013	good	good	1.7982	0.0067	good	good
112	19-57	0.3397	8	8	0.00040	0.0008	good	good	1.7982	0.0037	good	good
113	20-51	0.3394	4	3	0.00002	0.002	good	good	1.8020	0.008	good	good
114	20-57	0.3397	5	3	0.00007	0.0008	good	good	1.7969	0.0014	good	good
115	20-61	0.3396	5	3	0.00030	0.002	good	good	1.7978	0.0035	good	good
116	V29	0.34	4	3	0.00025	0.0020	good	good	1.7980	0.0007	good	good
117	V11	0.3394	5	5	0.00040	0.0017	good	good	1.8020	0.0014	good	good
118	19-43	0.3394	7	6	0.00015	0.0003	good	good	1.8010	0.006	good	good
119	22-32	0.3395	6	3	0.00020	0.0004	good	good	1.7993	0.003	good	good
120	22-47	0.3394	6	8	0.0003	0.0019	good	good	1.8000	0.0012	good	good
121	22-52	0.3395	4	5	0.00020	0.0001	good	good	1.8010	0.001	good	good
122	V15	0.3391	5	3	0.00010	0.0019	good	good	1.8010	0.005	good	good
123	22-42	0.3396	8	7	0.0004	0.0009	good	good	1.8004	0.005	good	good
124	22-21	0.3392	3	4	0.00040	0.0009	good	good	1.7981	0.0075	good	good
125	V18	**0.3388**	6	6	0.00015	0.0003	good	good	1.8000	0.002	good	good
126	20-48B	0.3395	5	7	0.0002	0.0004	good	good	1.7976	0.004	good	good
127	19-45	0.3391	7	3	**0.00060**	0.0011	good	good	1.7990	0.002	good	good
128	22-14	0.3399	4	8	**0.00070**	**0.0035**	good	good	1.8018	0.0009	good	good

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		STEM				SEAT			VALVE HEAD			
Quantity	Valve #	Stem Dim. .3400/.3392	Stem Ra 8uin	Seat Ra 8uin	Stem Straightness 0.0004	Seat Runout .002 A	Large Radius R.75 +\-.02	Seat Angle 60 +/-15	Head Diameter 1.803/1.793	Head Runout 0.01	Corner Radii .025/.040	Location from Datum .147/.138
129	20-50	0.3396	7	6	0.0004	0.0008	good	good	1.7989	0.0016	good	good
130	19-55	0.3394	4	5	0.00070	0.0035	good	good	1.7980	0.0066	good	good
131	20-19	0.3396	4	3	0.00050	0.0025	good	good	1.7960	0.0014	good	good
132	22-50	0.3393	7	5	0.0005	0.0018	good	good	1.7995	0.0028	good	good
133	20-48A	0.3395	8	7	0.00055	0.0011	good	good	1.8000	0.003	good	good
134	V8	0.3398	6	7	0.00070	0.002	good	good	1.8030	0.0008	good	good
135	22-20	0.3394	4	3	0.00060	0.0019	good	good	1.7989	0.0029	good	good
136	22-28	0.3398	4	5	0.00070	0.004	good	good	1.8019	0.0078	good	good
137	?	0.3394	5	3	0.00080	0.0013	good	good	1.7958	0.0032	good	good
138	22-58	0.3398	4	7	0.00100	0.004	good	good	1.7991	0.009	good	good
139	22-61	0.3397	6	6	0.00110	0.003	good	good	1.7980	0.0055	good	good
140	22-40	0.3397	4	6	0.00140	0.0045	good	good	1.7980	0.0032	good	good
141	20-43	N/G	8	5	0.00060	0.0012			1.8620	0.0018	large	
142	22-22	N/G	3	4	0.00010	0.0009			1.8640	0.0006	large	
143	22-49	N/G	4	3	0.00025	0.0013			1.8610	0.001	large	
144	22-66	N/G	4	4	0.00005	0.0005			1.7980	0.005	good	
145	V16	N/G	5	3	0.00010	0.0002			1.8620	0.0007	large	
146	19-52	Broke during pre-grind										
147	22-43	N/G	5	3	0.00040	0.0037	good	good	Chipped	0.003	good	good
148	V14	N/G	8	8	0.00020	0.0007	good	good	Chipped	0.0054	good	good
149	22-46	N/G										
150	20-26	N/G										

Double # valves

20-48	v-7
22-54	v-2

	125	good valves
	1	length problem
	1	keeper groove problem
	13	straightness and seat runout problem
	2	chipped or material problem
	8	no good (no seat, broken, etc.)
total	**150**	

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		VALVE END			KEEPER GROOVE				
Quantity	**Valve #**	**End Angle** 60 °	**Dist. from Datum** 7.405/7.395	**Parallelism** 0.001	**Dist. from Datum** 6.901/6.886	**Keeper profile**	**Keeper Ra** 8	**Keeper runout** 0.003	**Keeper Diameter** .300/.293
1	19-44	good	7.405	good	6.8955	good		0.0002	good
2	19-46	good	7.399	good	6.8925	good		0.0002	good
3	19-42	good	7.398	good	6.8905	good	5	0.0005	good
4	19-47	good	7.395	good	6.8965	good		0.0007	good
5	19-48	good	7.401	good	6.8925	good		0.0006	good
6	19-53	good	7.402	good	6.8945	good	5	0.0003	good
7	19-56	good	7.402	good	6.8945	good		0.0006	good
8	19-58	good	7.4	good	6.8915	good		0.0005	good
9	19-59	good	7.403	good	6.8945	good		0.0005	good
10	19-60	good	7.401	good	6.8925	good	4	0.0004	good
11	20-1	good	7.399	good	6.8905	good		0.0007	good
12	20-2	good	7.402	good	6.8955	good		0.0003	good
13	20-3	good	7.401	good	6.8925	good		0.0003	good
14	20-4	good	7.399	good	6.8905	good		0.0005	good
15	20-5	good	7.403	good	6.8935	good	5	0.0007	good
16	20-6	good	7.4	good	6.8915	good		0.0004	good
17	20-7	good	7.4	good	6.8915	good		0.0007	good
18	20-8	good	7.398	good	6.8915	good		0.0006	good
19	20-9	good	7.399	good	6.8915	good		0.0005	good
20	20-10	good	7.395	good	6.8905	good	4	0.0005	good
21	20-11	good	7.401	good	6.8945	good		0.0002	good
22	20-12	good	7.397	good	6.8925	good		0.0007	good
23	20-14	good	7.397	good	6.8925	good		0.0006	good
24	20-15	good	7.4	good	6.8905	good		0.0002	good
25	20-16	good	7.404	good	6.8955	good	4	0.0007	good
26	20-17	good	7.405	good	6.8975	good		0.0004	good
27	20-18	good	7.397	good	6.8985	good		0.0009	good
28	20-20	good	7.402	good	6.8925	good		0.0007	good
29	20-41	good	7.396	good	6.8975	good		0.0008	good
30	20-42	good	7.4	good	6.8925	good	4	0.0006	good
31	20-44	good	7.401	good	6.8945	good		0.0003	good
32	20-45	good	7.401	good	6.8945	good		0.0008	good

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		VALVE END			KEEPER GROOVE				
Quantity	Valve #	End Angle 60 °	Dist. from Datum 7.405/7.395	Parallelism 0.001	Dist. from Datum 6.901/6.886	Keeper profile	Keeper Ra 8	Keeper runout 0.003	Keeper Diameter .300/.293
33	20-46	good	7.402	good	6.8945	good		0.0006	good
34	20-47	good	7.4	good	6.8915	good		0.0001	good
35	20-49	good	7.398	good	6.8955	good	4	0.0008	good
36	20-52	good	7.394	good	6.8985	good		0.0007	good
37	20-58	good	7.396	good	6.8895	good		0.0003	good
38	20-59	good	7.4	good	6.8925	good		0.0007	good
39	20-60	good	7.397	good	6.8955	good		0.001	good
40	20-62	good	7.396	good	6.8945	good	5	0.0008	good
41	20-70	good	7.398	good	6.8965	good		0.0007	good
42	20-71	good	7.402	good	6.8945	good		0.0008	good
43	22-10	good	7.399	good	6.8915	good		0.0007	good
44	22-11	good	7.4	good	6.8915	good		0.0005	good
45	22-12	good	7.4	good	6.8915	good	4	0.0002	good
46	22-13	good	7.4	good	6.8915	good		0.0004	good
47	22-15	good	7.399	good	6.8915	good		0.0001	good
48	22-17	good	7.399	good	6.8905	good		0.0005	good
49	22-19	good	7.399	good	6.8905	good		0.0003	good
50	22-23	good	7.401	good	6.8925	good	4	0.0008	good
51	22-24	good	7.399	good	6.8905	good		0.0008	good
52	22-25	good	7.398	good	6.8905	good		0.0001	good
53	22-26	good	7.398	good	6.8905	good		0.0003	good
54	22-27	good	7.403	good	6.8945	good		0.0005	good
55	22-29	good	7.398	good	6.8905	good	4	0.0002	good
56	22-30	good	7.402	good	6.8935	good		0.0005	good
57	22-31	good	7.399	good	6.8925	good		0.0005	good
58	22-33	good	7.4	good	6.8915	good		0.0006	good
59	22-34	good	7.398	good	6.8895	good		0.0003	good
60	22-35	good	7.4	good	6.8925	good	4	0.0006	good
61	22-36	good	7.403	good	6.8945	good		0.0005	good
62	22-37	good	7.4	good	6.8925	good		0.0003	good
63	22-38	good	7.402	good	6.8935	good		0.0004	good
64	22-39	good	7.4	good	6.8915	good		0.0006	good

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		VALVE END			KEEPER GROOVE				
Quantity	Valve #	End Angle 60 °	Dist. from Datum 7.405/7.395	Parallelism 0.001	Dist. from Datum 6.901/6.886	Keeper profile	Keeper Ra 8	Keeper runout 0.003	Keeper Diameter .300/.293
65	22-41	good	7.398	good	6.8905	good	4	0.0006	good
66	22-44	good	7.403	good	6.8945	good		0.0006	good
67	22-45	good	7.395	good	6.8915	good		0.0005	good
68	22-51	good	7.397	good	6.8925	good		0.0005	good
69	22-54A	good	7.401	good	6.8935	good		0.0003	good
70	22-54B	good	7.401	good	6.8955	good	4	0.0004	good
71	22-55	good	7.399	good	6.8955	good		0.0002	good
72	22-56	good	7.396	good	6.8905	good		0.0006	good
73	22-57	good	7.404	good	6.8945	good		0.0003	good
74	22-59	good	7.399	good	6.8915	good		0.0006	good
75	22-60	good	7.401	good	6.8935	good	5	0.0001	good
76	22-62	good	7.396	good	6.8875	good		0.0002	good
77	22-63	good	7.4	good	6.8925	good		0.0005	good
78	22-64	good	7.395	good	6.8885	good		0.0004	good
79	22-65	good	7.401	good	6.8925	good		0.0005	good
80	22-67	good	7.398	good	6.8915	good	4	0.0005	good
81	22-68	good	7.402	good	6.8925	good		0.0005	good
82	22-69	good	7.396	good	6.8875	good		0.0003	good
83	V1	good	7.399	good	6.8905	good		0.0006	good
84	V2	good	7.399	good	6.8905	good		0.0005	good
85	V2A	good	7.399	good	6.8905	good	4	0.0002	good
86	V3	good	7.399	good	6.8925	good		0.001	good
87	V6	good	7.397	good	6.8895	good		0.0005	good
88	V7a	good	7.399	good	6.8905	good		0.0002	good
89	V7b	good	7.397	good	6.8905	good		0.0006	good
90	V10	good	7.401	good	6.8925	good	4	0.0006	good
91	V12	good	7.399	good	6.8925	good		0.0007	good
92	V13	good	7.399	good	6.8915	good		0.0004	good
93	V17	good	7.403	good	6.8945	good		0.0003	good
94	V19	good	7.4	good	6.8925	good		0.0003	good
95	V20	good	7.399	good	6.8915	good	4	0.0005	good
96	V21	good	7.401	good	6.8935	good		0.0005	good

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		VALVE END			KEEPER GROOVE				
Quantity	Valve #	End Angle 60 °	Dist. from Datum 7.405/7.395	Parallelism 0.001	Dist. from Datum 6.901/6.886	Keeper profile	Keeper Ra 8	Keeper runout 0.003	Keeper Diameter .300/.293
97	V23	good	7.4	good	6.8905	good		0.0003	good
98	V24	good	7.397	good	6.8905	good		0.0008	good
99	V25	good	7.397	good	6.8925	good		0.0006	good
100	V26	good	7.398	good	6.8935	good	5	0.0005	good
101	V27	good	7.4	good	6.8945	good		0.0007	good
102	V28	good	7.396	good	6.8915	good		0.0007	good
103	V30	good	7.398	good	6.8915	good		0.0007	good
104	V31	good	7.397	good	6.8925	good		0.0008	good
105	V32	good	7.397	good	6.8935	good	5	0.0007	good
106	V33	good	7.397	good	6.8895	good		0.0004	good
107	V34	good	7.397	good	6.8905	good		0.0005	good
108	V35	good	7.4	good	6.8905	good		0.0003	good
109	V37	good	7.398	good	6.8905	good	3	0.0003	good
110	19-50	good	7.401	good	6.8935	good		0.0001	good
111	19-54	good	7.399	good	6.8915	good		0.0005	good
112	19-57	good	7.397	good	6.8895	good		0.0001	good
113	20-51	good	7.395	good	6.8945	good		0.001	good
114	20-57	good	7.399	good	6.8915	good	6	0.0005	good
115	20-61	good	7.396	good	6.8965	good		0.0005	good
116	V29	good	7.399	good	6.8945	good		0.0008	good
117	V11	good	7.4	good	6.8975	good		0.001	good
118	19-43	good	7.4	good	6.8915	good	6	0.0002	good
119	22-32	good	7.396	good	6.8935	good		0.001	good
120	22-47	good	7.395	good	6.9005	good		0.0003	good
121	22-52	good	7.403	good	6.8935	good		0.0004	good
122	V15	good	7.4	good	6.8925	good		0.0002	good
123	22-42	good	7.397	good	6.8915	good		0.0003	good
124	22-21	good	7.403	good	6.8925	good		0.0012	good
125	V18	good	7.401	good	6.8905	good	5	0.0001	good
126	20-48B	good	7.41	good	6.8905	good		0.0008	good
127	19-45	good	7.398	good	6.8905	good		0.0003	good
128	22-14	good	7.402	good	6.9005	good		0.0005	good

NOTE: All dimensions are in inches unless otherwise noted.

ACMT VALVE INSPECTION REPORT

		VALVE END			KEEPER GROOVE				
Quantity	Valve #	End Angle 60 °	Dist. from Datum 7.405/7.395	Parallelism 0.001	Dist. from Datum 6.901/6.886	Keeper profile	Keeper Ra 8	Keeper runout 0.003	Keeper Diameter .300/.293
129	20-50	good	7.396	good	6.9235	good		0.001	good
130	19-55	good	7.397	good	6.8895	good	5	0.0003	good
131	20-19	good	7.393	good	6.8945	good		0.0004	good
132	22-50	good	7.399	good	6.8935	good		0.0007	good
133	20-48A	good	7.397	good	6.8995	good		0.0004	good
134	V8	good	7.4	good	6.8915	good	6	0.0008	good
135	22-20	good	7.396	good	6.8905	good		0.001	good
136	22-28	good	7.42	good	6.9255	small		0.0006	small
137	?	good	7.396	good	6.8915	good		0.001	good
138	22-58	good	7.398	good	6.8915	good		0.0012	good
139	22-61	good	7.396	good	6.8935	good	5	0.0007	good
140	22-40	good	7.4	good	6.8905	good		0.001	good
141	20-43	good	#VALUE!		#VALUE!				
142	22-22	good	#VALUE!		#VALUE!				
143	22-49	good	#VALUE!		#VALUE!				
144	22-66	good	#VALUE!		#VALUE!				
145	V16	good	#VALUE!		#VALUE!				
146	19-52								
147	22-43	good	7.397	good	6.8875	good		0.0008	good
148	V14	good	7.398	good	6.8905	good		0.0006	good
149	22-46								
150	20-26								

Double # valves

20-48	v-7
22-54	v-2

NOTE: All dimensions are in inches unless otherwise noted.

APPENDIX C

Vendor C (Centerless Grinding) Dimensional and Metrology Data of Machined Valves*

*12 of the 45 valves ground by Vendor C as part of the production demonstration set.

Sheet 1 of 3

INSPECTION REPORT

Request # 98020 0218　　Drawing # D10190　　Description Valves

Quantity 45　　Inspector DM + KC　　Date 2-12-98

Identification Number				
Feature	4	5	6	7
1.793/1.803	1.8027	1.8015	1.8011	1.8015
0.147/0.138	0.147	0.1463	0.1463	.1468
0.301/0.291	0.300	0.2972	.2991	.2977
6.901/6.886	6.8891	6.886	6.8913	6.8914
7.405/7.395	7.396	7.3987	7.3997	7.4012
60°±2	60.01	59.87	60.14	60.09
60°±15'	60.07	60.12	60.10	60.10
30±15'	29.22	29.47	28.77	29.20
R0.75±2	0.744	0.7465	.7485	.7489
R0.056/0.050	.0514	.0506	.050	0492
R0.005/0.010	.0096 KC ~~.011~~	0116	.0111	.0102
0.300/0.293	0.295	0.2969	.2964	.2965
0.280±0.005	0.280	0.277	.2793	.2779
⊥0.001/A	.00034	.000029	.0002	.00012
↗0.013/A	.00018	.0004	.00067	.00028
↗0.010/A	.00019	.00043	.00025	.00028
↗0.002/A	.00027	.0004	.00056	.00034
— 0.0004	.000077	.00089	.000064	.000065
V8 stem	3.4	3.63	4.79	4.63
V8 seat	5.11	5.36 ~~4.74~~	7.06	4.74
V8 angle	5.95	4.74	5.86	5.26
V8 radius	5.8	6.9	7.07	6.65
0.3400/0.3392	.33975-.33985	.33975-.3399	.33965-.3398	.3397-.3398

Sheet 2 of 3

INSPECTION REPORT

Request # 980200218 Drawing # D10190 Description Valves
Quantity 45 Inspector DM + KPC Date 2-12-98

	Identification Number				
	Feature	8	9	10	11
	1.793/1.803	1.8012	1.8008	1.8012	1.8011
	0.147/0.138	.1470 ~~.1472~~	.1466 .1476	.145	.1464
	0.301/0.291	.3016	~~.3016~~ .3035	3009 KPC ~~.3012~~	.3008
	6.901/6.886	6.8989	6.8908	6.8939	6.8911
	7.405/7.395	7.4004	7.3994	7.3974	7.3997
	60°±2	60.01	60.15	59.97	60.14
	60°±15'	59.93	60.03	60.00	59.99
	30±15'	29.4	29.2	29.22	29.16
	R0.75±2	.7491	.751	.7473	.7472
	R0.056/0.050	.0499	.0499	.0499	.0497
	R0.005/0.010	.0088	.0086	.0085	.0095
	0.300/0.293	.2963	.2964	.2959	.2962
	0.280±0.005	.2792	.280	.2789	.2808
4	⊥ 0.001 A	.00052	.0005	.00006	0.00011
1	↗ 0.013 A	.00048	.00052	.00033	0.00055
2	↗ 0.010 A	.00075	.0012	.0008	0.00063
3	↗ 0.002 A	.00036	.0006	.0004	0.00044
5	— 0.0004	.00028	.00033	.0001	0.0001
	V8 stem	4.01	4.14	5.35	5.20
	V8 seat	5.03	4.96	5.24	4.40
	V8 angle	6.97	7.01	7.91	5.86
	V8 radius	6.81	5.59	8.08	5.81
	0.3400/0.3392	.33975-.33995	.33975-.33985	.33985-.3400	.3399-.3400

INSPECTION REPORT

Request # 980200218 | Drawing # D10190 | Description Valves
Quantity 45 | Inspector DM +KC | Date 2-12-98

Identification Number				
Feature	12	13	14	15
1.793/1.803	1.8009	1.8005	1.8016	1.802
0.147/0.138	.1461	.1431	.1453	.1465
0.301/0.291	.301	.2992	.2991	.3005
6.901/6.886	6.8918	6.8848	6.8916	6.8915
7.405/7.395	7.400	7.4029	7.398	7.4002
60°±2	60.04	60.17	60.13	60.06
60°±15'	60.00	59.95	60.08	60.07
30±15'	29.36	28.81	28.93	29.19
R0.75±2	.7507	.7488	.7485	.7478
R0.056/0.050	0507	.0503	.0509	.0503
R0.005/0.010	.0078	.0055	.0063	.0053
0.300/0.293	.295	.2966	.2963	.2958
0.280±0.005	.2792	.2794	.280	.281
⊥0.0011A	.000039	.000022	.00001	.000086
↗0.0013 A	.00011	.00027	.00018	.000052
↗0.010/A	.00064	.00071	.00042	.000362
↗0.002/A	.00049	.00027	.00039	.00045
— 0.0004	.00025	.00035	.00020	.00018
√8 stem	4.57	4.00	6.05	4.11
√8 seat	5.39	5.58	5.71	6.20
√8 angle	6.48	6.42	5.14	5.38
√8 radius	7.39	6.67	6.57	7.26
0.3400/0.3392	~~.3395-.3398~~ .33985-.3400	.3395-.3398	.3395-.33975	.33965-.3400

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