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A Strategy for DoD Manufacturing Science and Technology R&D in Precision Fabrication

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This report provides a strategy for DoD-sponsored R&D applied to advanced manufacturing processes. The strategy covers the precision fabrication processes of forming, material removal, heat and surface treatment, and joining. To meet the DoD objective of "technology for affordability," we recommend that R&D be focused on flexible manufacturing, process modeling, and sensor-based process control. We conclude that overall DoD funding for R&D applied to precision fabrication processes is disproportionately low. In addition to increasing the relative amount of precision fabrication R&D funding, DoD needs to strike a balance between R&D for military-unique requirements and that for broader, cost-reducing technologies.

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Executive Summary

DoD's Manufacturing Science and Technology (MS&T) Program sponsors R&D to improve advanced manufacturing processes in four major areas: precision fabrication, electronics processing, composite materials processing, and manufacturing systems. Precision fabrication – the accurate and repeatable processing of engineered materials into structures and shapes that are later assembled into subsystems and end products – includes processes that join, reshape, or consolidate materials; change their form; reduce their mass; or change their structure.

In 1993, precision fabrication R&D received $49 million, or about 9 percent of the $569 million the Program allocated to process development. By way of comparison, electronics processing received $472 million, or 83 percent. For the reasons given below, we recommend that precision fabrication R&D funding be increased to $128 million annually or – if MS&T funds are constrained to the degree that such an allotment is not feasible – that funding for the three nonelectronics areas combined be boosted from 17 percent of the program to at least 50 percent.

One guideline for determining the level of R&D funding is to express it as a percentage of sales. In the years 1986 - 1989, total R&D in U.S. manufacturing industries averaged 4.7 percent of sales. The Federal portion, included in that number, averaged 1.6 percent. In contrast, current DoD funding for precision fabrication R&D is low, representing only 0.6 percent of the $8 billion DoD spends annually on precision fabrication manufacturing activities. Our $128 million recommendation is derived by applying the Federal R&D average of 1.6 percent of sales to that $8 billion figure.

In support of the notion that precision fabrication R&D funding should be increased to be proportional to overall DoD R&D funding, we note that precision fabrication activities display relatively high "shop-floor" manufacturing labor costs and relatively low "above-the-shop-floor" mechanical engineering and toolmaking costs. While high cost itself does not necessarily indicate large opportunity for savings, that division of costs does indicate that many advanced features of electronics manufacturing – such as design for automation and automated process control – have yet to be fully exploited in the more traditional areas of precision fabrication. Hence our belief that significant returns are to be gained by focusing additional R&D funding on precision fabrication.

Once overall funding for precision fabrication R&D has been determined, the funds must be allocated to technical areas within precision fabrication. By consulting industry associations, private companies, and technical experts, we have sought to identify opportunities for improving quality, increasing productivity, and reducing cost by applying precision fabrication R&D. While the range of responses has been understandably broad, three technical areas stand out as especially promising: *flexible manufacturing*, *process modeling*, and *sensor-based control*.

Flexible manufacturing is the ability to fabricate different types and quantities of parts economically to meet varying demands with an unchanging set of machinery. Flexible manufacturing technologies make small batches more economical and lower the sensitivity of unit costs to volume. We recommend that the MS&T Program sponsor R&D to improve techniques for setup (e.g., workholding, tool setting, aligning, checking out); expand the capability of individual processes so that a single piece of equipment can process a larger variety of parts; and develop process equipment that performs multiple functions.

Process modeling involves the use of analytical tools to improve the understanding of the physics and chemistry of precision processes. We recommend that MS&T attention be directed at developing computer simulations for predicting process behavior that is not well understood or process parameter values that are outside the realm of experience; speeding the validation of experimental process results and their incorporation into data bases; providing information needed for automated process planning and control; and updating data on materials whose behavior is well known, in order to reflect advances in process capability. Taking these steps can dramatically reduce scrap and rework – especially in first-article production – and the need for manual inspection of subsequent articles.

Sensor-based control involves automatically detecting and compensating for changes that affect a process's precision. Conditions that can be monitored by sensors include workpiece conditions (e.g., geometry, strain, and heat profile), tool condition (e.g., wear and breakage), workholding condition (e.g., offset, alignment, and rigidity), and equipment condition (e.g., vibration, power consumption, and bearing temperature). Process sensors can be integrated with machines, machine controllers, and manufacturing engineering data bases. They can take readings at much smaller time intervals and with much higher resolution than is possible with manual inspection techniques. Sensors help reduce process variability, help reduce the need for process interruption (for manual inspection), and can reduce the amount of scrap due to excess material removal.

In addition to supporting technologies that improve the overall affordability of defense products, the MS&T Program must satisfy the demands of high-priority weapons program offices (e.g., F-22, F/A-18 E/F aircraft) for process technologies necessary to meet program performance, cost, and schedule goals. Also, in the absence of commercial competition, MS&T must ensure that process capabilities unique to defense manufacturing (e.g., the production of ammunition and large cannon) are advanced. At present, DoD has little information to guide the assigning of priorities to weapon system and defense-unique requirements for precision fabrication R&D. We recommend that the Services meet and exchange such information as part of future MS&T planning.

Currently, 66 percent of DoD's precision fabrication R&D is spent to satisfy high-priority weapons-related and defense-unique process objectives; 8 percent is spent in the flexible manufacturing area; 23 percent on process modeling; and 3 percent on sensor-based control. We recommend that the MS&T Program management establish guidelines for balancing weapons-related and defense -unique process objectives with the broader "technology for affordability" objective established by the Director of Defense Research and Engineering. We further recommend that until such guidance is established and until the Services collectively identify weapon-system and defense-unique requirements for precision fabrication R&D, funding for flexible manufacturing, process modeling, and sensor-based control be increased to 50 percent of the precision fabrication budget and that all three of these technical areas receive equal funding. Given the $128 million that precision fabrication R&D would receive if funded as recommended, each area would receive $21 million annually. The remaining $65 million should be applied to weapon-system and defense-unique process R&D requirements.

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Chapter 1

Background

Purpose

The Manufacturing Science and Technology (MS&T) Program within DoD sponsors R&D to improve advanced manufacturing processes. Despite the decline in defense acquisitions, weapon designers continue to create advanced products that must be fabricated from a new generation of exotic materials, including ceramics and metal-matrix composites. These products are not solely those destined for new weapons systems; often they are upgrades or redesigned spare parts being manufactured for insertion into already fielded systems. R&D applied to precision fabrication technologies can enhance the manufacture of products from new materials and can give new efficiencies and precision to processes that transform established materials. The study embodied in this report was undertaken to update the MS&T Program's strategy for precision fabrication R&D. Appendix A summarizes progress in precision fabrication R&D since the previous plan was prepared in 1991. Appendix B discusses why advancing precision fabrication processes is in DoD's interest.

The Precision Fabrication Committee (PFC)[1] is an ad hoc working group in DoD's MS&T Program charged with developing and implementing this strategy. Within DoD, precision fabrication is referred to as a subthrust within the Defense Research and Engineering Director's management thrust "technology for affordability" (also called Thrust 7).[2] The PFC draws members from OSD, the three Services, DLA, the Ballistic Missile Defense Organization, the Department of Energy, the National Science Foundation (NSF), and the Department of Commerce's National Institute of Standards and Technology (NIST). In addition, the PFC has established advisory relationships with the Association for Manufacturing Technology (AMT) and the Society of Manufacturing Engineers (SME). Appendix C lists the MS&T projects that are within the PFC's purview.

The MS&T Program's objective in funding precision fabrication R&D is to ensure the availability of production technologies that can provide manufactured goods (ranging from major weapons to spare parts) meeting DoD's performance, cost, and schedule requirements. Process improvements aimed at meeting

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[1] At the 1993 Defense Manufacturing Conference (1 December 1993), Dr. William Kessler (Director, Air Force Manufacturing Technology) announced that the MS&T Program's technical committees had been folded into the Joint Logistics Commanders' Project Reliance. Under that organization, the Precision Fabrication Committee described in this report will be known as the Metals Processing and Manufacturing Sub-panel.

[2] See U.S. Department of Defense, Director of Defense Research and Engineering, *Defense Science and Technology Strategy*, July 1992 (available by calling 703-697-5737) for a description of management thrusts.

environmental and safety regulations are also sought. The management activities required to effectively meet the MS&T program objective are the following:

- Allocation of MS&T funds to major process areas (of which precision fabrication is one)
- Allocation of funds within those areas to technical areas (including defining which technical areas are appropriate)
- Allocation of technical area funds to specific projects
- Administration of current projects
- Dissemination of results.

These activities take place continuously and in parallel; they are an ongoing process of assessing industry's technology needs, identifying Government's (and DoD's) appropriate role, balancing R&D requirements with resources, and funding projects. This strategic plan covers the first two steps.

Scope

Precision fabrication is the accurate and repeatable processing of engineered materials into structures and shapes that are later assembled into subsystems and end products. Over 70,000 different grades of engineered materials have been developed. These include over 25,000 different steels, over 200 standard copper alloys, and over 75 common wrought aluminum alloys.[3] Engineered materials come in a variety of shapes, including ingot, powder, sheet, wire, and bar. These materials and forms are the input to precision fabrication processes.

Precision fabrication includes shop-floor fabrication processes and the engineering of those processes. A specific shop-floor process consists, at a minimum, of a workpiece, a machine, ancillary equipment (tooling), and labor to perform the process. Frequently, a process also includes controlling computers. Within the scope of precision fabrication are processes that join, reshape, or consolidate materials; change their form; reduce their mass; or change their structure. Also included are the metrology associated with these processes, the manual labor and skills required for them, the requisite primary and ancillary equipment, and computers and machine controllers.[4]

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[3] R. Thomas Wright, *Exploring Manufacturing* (South Holland, Ill: The Goodheart-Wilcox Company, Inc., 1985), pp. 21-22.

[4] Adapted from a taxonomy developed by the Unit Manufacturing Process Research Committee of the Manufacturing Studies Board.

The number of precision fabrication processes is uncountable and ever-changing, since new processes are constantly emerging and others are becoming obsolete. Table 1-1 gives examples of these processes and associated resources. While the processes are commonly associated with metalworking, they are applied also to the transformation of plastics, ceramics, and composites.

Table 1-1.
Examples of Precision Fabrication Processes and Resources

Category	Examples	Category	Examples
Processes that change *form*	Squeeze casting	Processes that *reshape*	Press forming
Processes that *consolidate*	Hot isostatic pressing Sintering	Processes that reduce *mass*	Broaching Water-jet cutting Milling Diamond turning
Processes that change *structure*	Heat treating Annealing Chromizing Laser hardening	Processes that *join*	Brazing Soldering Friction welding
Metrology	Sensors Gauges Micrometers Comparators Coordinate measuring machines	Manual *labor* and skills	Blueprint reading Algebra Trigonometry Computer operation *Safety and first aid* Machine operation and maintenance
Primary equipment	Machine tools Ovens Presses Robots	*Ancillary equipment*	Molds and dies Cutting tools Hand tools Jigs Fixtures Lubricants
Machine *intelligence*	Cell controllers Machine controllers Process models Expert systems		

Precision fabrication includes metrology directly associated with monitoring, controlling, and evaluating its processes. It does not include testing for product performance not directly related to a specific manufacturing process. Precision fabrication includes only those "assembly" processes in which materials are "irreversibly" joined, such as welding, brazing, and adhesive bonding. It does not include manual assembly, assembly with fasteners, or riveting. These distinctions are somewhat arbitrary and, in some specific cases, should be relaxed to permit adequate evaluation of project alternatives (for example, comparing welding to drilling and riveting).

MANUFACTURING SCIENCE AND TECHNOLOGY (MS&T) TECHNICAL COMMITTEES

The MS&T program has four technical committees, each responsible for planning R&D in a "subthrust" under the "technology for affordability" R&D thrust. In addition to precision fabrication, the committees cover manufacturing systems, electronics manufacturing, and composite materials processing and fabrication. The manufacturing systems committee addresses technologies for "above the factory floor" manufacturing support activities. The electronics manufacturing committee covers material and device production as well as the packaging and integration of the devices into electronics systems. The composites committee focuses on polymer-matrix materials (as opposed to ceramic- or metal-matrix materials).

It is important that the PFC interact with the other committees. With the manufacturing systems committee, the important interactions are between shop-floor processes and supporting engineering and quality activities. Also, the information interchange (including underlying data standards and communications standards) between machine and cell controllers and other business systems is an area of mutual interest. R&D opportunities for the processing of composite materials, particularly those based on polymer matrices, overlap the purview of the PFC and the composites committee. The composites committee coordinates R&D on materials processing of polymer-matrix composites: molding, laying up, bonding, and consolidation. The PFC's scope can include R&D applied to the secondary processing (e.g., machining) of those composites.

REPORT ORGANIZATION

Chapter 2 presents our findings and recommendations. Chapter 3 discusses the technical areas we recommend that the MS&T Program focus on to promote the affordability of defense manufactured goods. The three appendices provide additional background material and project details.

CHAPTER 2

Findings and Recommendations

In this chapter, we examine the allocation of MS&T funds to the general subject of precision fabrication and, in turn, the allocation of those precision fabrication funds to technical areas.

ALLOCATION OF MS&T FUNDS TO PRECISION FABRICATION

Ideally, all MS&T projects would be awarded competitively from a single pool of R&D funds. Practically, however, it is very difficult to compare specific benefits on individual projects as diverse as thin-film crystal growth and linear friction welding ("common denominators," such as return on investment, are notoriously inaccurate). Historically, each Service (and DLA) has developed its own manufacturing R&D program independently. Beginning in 1991, OSD began to coordinate manufacturing R&D planning by focusing on opportunities for cost-reducing process technologies of joint Service interest. Currently, MS&T process technology funds are allocated first to major process areas and then to technical areas. The MS&T major process areas correspond to the committee structure discussed in Chapter 1 (precision fabrication, electronics processing, composite materials processing, and manufacturing systems). The "top-down" allocation to precision fabrication centers on two questions:

- How much money should the overall MS&T program allocate to precision fabrication?
- Given likely restrictions on the total amount of money available to MS&T, what portion of the available funds should precision fabrication receive?

While no equation exists to answer these questions, data are available to support qualitative decisions.

The precision fabrication process area received between $45 million and $49 million in 1993. This represents between 8 and 9 percent of the $569 million MS&T funding for process technology development.[1] In contrast, electronics

[1] Defense Manufacturing Science and Technology Integration Plan, 21 December, 1992, p. 6. That plan identifies $45 million in precision fabrication funding; our calculations indicate the level is $49 million. Neither figure includes the $45 million Congressionally-directed grant to the National Center for Manufacturing Sciences, some of which is used to conduct precision fabrication R&D.

processing received 83 percent of the MS&T program funds. Figure 2-1 shows the breakout of 1993 MS&T funds by process area.

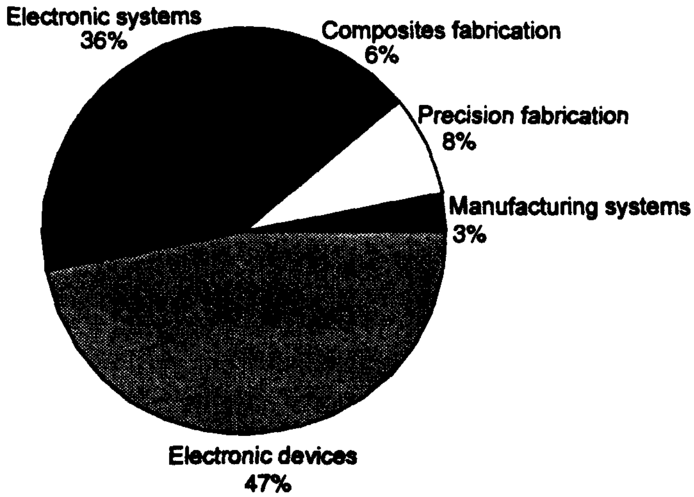

Figure 2-1.
Breakout of 1993 MS&T Funds by Process Area

One guideline for the level of R&D funding is to express R&D as a percentage of sales. Industries tend to set a level that best balances their short-term objectives (e.g., operating profits) with their long-term objectives (e.g., market share and new product introductions). Table 2-1 shows Federal, industry, and total R&D spending for the decade ending in 1989.

Table 2-1.
Federal, Industry, and Total R&D Spending (Expressed as a Percentage of Net Sales) for the Decade Ending in 1989

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Federal	0.9	0.9	1.2	1.3	1.3	1.4	1.5	1.5	1.6	1.6
Industry	2.1	2.2	2.6	2.6	2.6	3.0	3.2	3.1	3.1	3.1
Total	3.0	3.1	3.8	3.9	3.9	4.4	4.7	4.6	4.7	4.7

Source: Research and Development in Industry, National Science Foundation, 1989, pp. 75 – 79.

For the period 1986 to 1989, total R&D in U.S. manufacturing averaged 4.7 percent of sales. The Federal portion of R&D, included in that number, averaged 1.6 percent of sales.

From this perspective, DoD funding for precision fabrication R&D is low, representing 0.6 percent of precision fabrication "sales" to defense. In 1991, all private-sector manufacturing for defense totaled $96 billion (FY93 dollars).[2] Of this, precision fabrication activities on the factory floor consumed 11 percent, or $11 billion (see Figure 2-2).

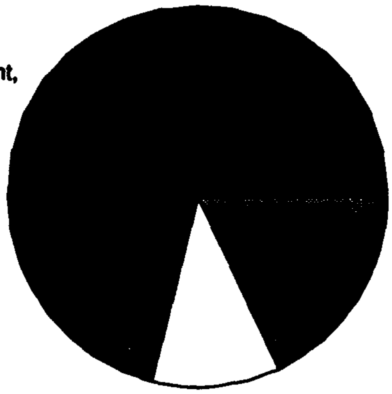

Figure 2-2.
Distribution of Defense Industry Activity Costs

Allowing for a 25 percent decline in defense acquisition since 1991, precision fabrication activities now consume roughly $8 billion of annual defense outlays. The $49 million precision fabrication R&D program in 1993 represents 0.6 percent of this $8 billion. If DoD funding for precision fabrication R&D were at the Federal average of 1.6 percent of sales, the program would receive 1.6 percent of $8 billion, or $128 million.

We recommend that the overall MS&T funding allocation be reviewed and that the precision fabrication process area allotment be increased to $128 million per year. In the event that such an allotment is not feasible, we recommend that R&D for non-electronics processes, including precision fabrication, be boosted from 17 percent of the program to at least 50 percent. While cost is not in itself an indicator of opportunity, precision fabrication activities display relatively high shop-floor labor costs and relatively low above-the-shop-floor costs, such as those for mechanical engineering and toolmaking. For example, the dollar ratio of factory floor precision fabrication workers to mechanical engineers is 4.8:1, whereas the ratio of factory floor electronics process workers to electrical engineers is 1:1.1.[3] This suggests that design-for-automation, automated process control, and other cost-decreasing, quality-increasing characteristics often associated with electronics manufacturing have yet to be fully exploited in precision fabrication.

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[2] LMI Report NT301R1, *The Defense Manufacturing Base: Activity-Based Cost Profiles and Their Implications for Funding Manufacturing Technology,* Eric L. Gentsch, et al. January 1992.

[3] Ibid.

ALLOCATION OF PRECISION FABRICATION FUNDS TO TECHNICAL AREAS

The MS&T Program is meant to augment, not replace, private industry's R&D funding. MS&T spending is appropriate when R&D is too risky for private investment or when the defense acquisition environment discourages such investments (for example, the issuing of sole-source development contracts that are unlikely to lead to production). The allocation of precision fabrication funds to technical areas centers on three questions:

- Into what technical areas should precision fabrication opportunities be cataloged to best facilitate project selection?
- What amount of funding should each technical area receive?
- Given limits on total funding, what percentage of precision fabrication funds should be allocated to each technical area?

The MS&T Program must respond to a variety of "customers" who place demands on it. MS&T must satisfy the demands of high-priority weapon program offices (e.g., F-22, F/A-18 E/F aircraft) for process technologies necessary to meet program performance, cost, and schedule requirements. Also, in the absence of commercial competition, MS&T must ensure that process capabilities unique to defense manufacturing (e.g. production of ammunition and large-bore cannon) are advanced. Finally, MS&T must strive to infuse into private industry the latest technologies for increasing productivity and quality. Currently, little information has been assembled in any central repository to prioritize weapon system and DoD-unique requirements for precision fabrication R&D. We recommend that the Services meet and exchange such information as part of future MS&T planning.

The MS&T Program must also strive to infuse into private industry the latest technologies for increasing productivity and quality. DoD calls this "technology for affordability." From industry associations, private companies, and technical experts, we have collected ideas about opportunities for precision fabrication R&D to reduce cost. All feel that the major objectives driving the R&D should be reduction of product development lead time and an increase in factory throughput. Most would like to see industry procure state-of-the-art equipment (e.g., laser drills and CNC spiral bevel cutter/grinders), but often such equipment is found to be too costly and too difficult to justify. All identified process sensing and control (variously referred to as process monitoring or adaptive control) as highly important to the efficient production of small lots to tight tolerances. Several sources pointed to reducing setup time as an important element of overall time reduction, observing that setup consumes 20 to 25 percent of machine operators' time.

While the range of specific technical suggestions (e.g., reduce porosity in aluminum castings) is understandably broad, given the many materials and processes that comprise precision fabrication, the concepts and objectives that emerged can be grouped into these technical areas:

- Flexible manufacturing
- Process modeling
- Sensor-based control.

We summarize these technical areas here; more complete descriptions are contained in the following chapter. Flexible manufacturing is a factory's rel ability to fabricate different types and quantities of parts economically, to varying demands while still using the same collection of machines. Flex manufacturing technologies make small batches more economical and lower the sensitivity of unit costs to volume. We recommend that the MS&T program sponsor R&D to:

- Improve techniques for setup (workholding, tool setting, alignment, and check-out)
- Expand the capability of individual processes so that a single piece of equipment can process a larger variety of parts
- Develop process equipment that performs multiple functions.

Process models include studies, tools, and techniques for improving the understanding of the physics and chemistry of precision processes. We recommend that MS&T attention be directed at:

- Developing computer simulations for predicting material process behavior that is not well understood or process parameter values that are outside the realm of experience
- Speeding the validation and compilation of experimental process results into data bases
- Providing the level of information needed for automated planning and control
- Updating data on materials whose process behavior is well known to reflect advances in process capability.

These capabilities can dramatically reduce scrap and rework, especially on the first article, and the need for manual inspection and help nable "one-start, one-part" production of subsequent articles.

Sensor-based control is the technical area dedicated to automatically detecting and compensating for changes that affect a process's precision. Types of process conditions that can be monitored by sensors include:

- Workpiece condition (e.g., geometry, strain, heat profile)
- Tool condition (e.g., wear, breakage)
- Workholding condition (e.g., offset, alignment, rigidity)
- Equipment condition (e.g., vibration, power consumption, bearing temperature).

Process sensors can be integrated with machines, machine controllers, and manufacturing engineering data bases. They can take readings at much smaller time intervals and with much higher resolution than is possible with manual inspection techniques. The use of sensors can help reduce process variability, can reduce the need for process interruption (for manual inspection), and can reduce the amount of scrap due to excess material removal.

Currently, 66 percent of DoD's precision fabrication R&D is spent to satisfy high-priority, weapons-related, defense-unique process objectives; 8 percent is spent in the flexible manufacturing area; 23 percent is spent on process modeling; and 3 percent on sensor-based control. We recommend that the MS&T program management establish guidelines for balancing weapons-related and defense-unique process objectives with the broader "technology for affordability" objective established by the Director of Defense Research and Engineering. We recommend that until such guidance is established and until the Services collectively identify weapon-system and defense-unique requirements for precision fabrication R&D, funding for flexible manufacturing, process modeling, and sensor-based control be increased to 50 percent of the precision fabrication budget and that all three areas receive equal funding. Given the $128 million that precision fabrication R&D would receive if funded as recommended, each technical area would receive $21 million annually. The remaining $65 million should be applied to weapon-system and defense-unique process R&D requirements.

Chapter 3

Technical Area Descriptions

In this chapter, we describe the three technical areas where we believe particularly high payoffs are to be gained from pursuing the PFC's "technology for affordability" objective: flexible manufacturing, process modeling, and sensor-based control. Because these terms by themselves are subject to varying interpretation in the defense community, we caution readers to consider the descriptions, goals, and benefits we present for each area as indicative of our proposed R&D agenda, rather than focusing simply on just the technical area title.[1]

Flexible Manufacturing

Description

"Flexible manufacturing" has many definitions and means different things to different people. A high-level definition on which most people would agree is "a factory's relative ability to economically fabricate different types and quantities of parts, to varying demand profiles, using the same collection of machines." Flexible manufacturing was born from the high interest rates of the late 1970s. Until then, factories had traditionally relied on large in-process inventories to provide a buffer against uncertainties (such as late deliveries, machine breakdowns, and uneven customer demand). In the late 1970's, to save interest expense, many companies trimmed inventories by moving production items faster through the shop. This, however, had the downside of moving large amounts of high-value-added inventory into finished stores. The next step (starting around the mid 1980s) was to cut the number of parts per batch released to the floor. Fewer parts per batch meant that each batch would flow through the shop faster, and so finished goods inventories could be lower without sacrificing customer service.

This change in operating doctrine solved one problem but created another: product costs went up, for three reasons — higher fixed costs, more scrap and rework, and lower machine capacity. When fewer parts were released per batch, more batches of any given product had to be run per year. Because each batch has a fixed cost for machine setup (generally independent of the processing cost), more fixed cost had to be allocated across the same production volume. Because more batches were being run, the aggregate amount of adjustment and experimentation required to get the first good part out of a batch (sometimes referred

[1] For example, many readers may interpret "process modeling" to mean the functional analysis (IDEF modeling) of a generic business practice. In the context of precision fabrication, however, "process modeling" refers to a mathematical or computer representation of a physical process, such as casting.

to as "learning") increased, as did the amount of scrap and rework. Finally, more time spent setting up meant that less time was available for processing – effective machine capacity became lower. For machines that were fully utilized (so-called bottlenecks), this meant that a company would have to buy more machines just to maintain steady output.

Today, interest rates are low again. But few companies are willing to return to large in-process inventories. They have found that "leaner," small-batch production buys a time advantage and lowers inventories. Because manufacturers can flow goods through the factory faster than before, they can be more responsive to uncertain and ever-changing customer demand. In many industries, ranging from apparel to pocket pagers, response time in delivering both current and new products is the deciding competitive factor.

Manufacturing managers want to keep inventories low, and they want to produce small batches quickly and economically. The schemes they use to do this are collectively referred to as "flexible manufacturing." Just as there is no standard definition for flexible manufacturing, there is no fixed set of requirements for a flexible manufacturing line. Nevertheless, many manufacturing operations that aspire to flexibility share the following design goals:

- A *cellular configuration* designed around similar part types rather than around similar machine types. (Also referred to as group technology or a product layout, this configuration puts all the machinery necessary to produce a given part – for example, a gear – in the same department. In traditional, process-oriented factory layouts, all drills were in one department, mills in another, etc.).

- *Workers trained* to run various pieces of equipment, and work rules (particularly in union shops) allowing personnel transfer across workstations and skill grades.

- *Smaller batch sizes* than in conventional mass production.

- *Just-in-time* delivery practices, from parts suppliers to a line, between workstations in the line, and to downstream assemblers.

- *Electronic interchange* of data between the factory floor and technical (e.g., engineering) and business (e.g., scheduling and payroll) computer systems.

To this list, some proponents of flexibility would add automation, ranging from individual computer-controlled machines to complete computer/robotic integration of processing, material handling, and inspection. Automation must be approached with caution, however, because it can raise fixed costs and breakeven points, thereby making unit costs highly sensitive to changes in demand and actually decreasing flexibility.

Goals

The PFC's goals for flexible precision fabrication should be to develop technologies that make small batches more economical and that lower the sensitivity of unit costs to changes in demand. The three primary approaches to meeting this goal are as follows:

- Improve techniques for setup: workholding, tool setting, alignment, and check-out
- Expand the capability of individual processes so that a single piece of equipment can process a larger variety of parts
- Develop process equipment that performs multiple functions.

While none of these ideas is new, challenging technical opportunities remain. Improved techniques for setup might include adaptive fixturing and the use of electrically or mechanically sensitive fluids.[2] Expanding the capability of individual processes might entail modular tables that accommodate a wider range of part geometries, or else new drive mechanisms that operate in a wider band (e.g., to higher speeds). While machining centers currently perform multiple functions, opportunities continue to emerge, such as incorporating lasers to preheat material.[3]

New technologies in these areas must take into consideration the people who will have to operate the equipment. In particular, they should be oriented to workers who are trained as generalists and are not devoted solely to one type of equipment. This can be accomplished through standard orientations, configurations, training modes, and menu-driven control interfaces.

For many companies, the initial drive to flexible manufacturing does not require technical development. There are, however, limits to what can be achieved by rearranging the factory and modifying scheduling and dispatching procedures. The PFC should address the technical challenges that remain after common-sense and off-the-shelf products have been applied. Many of these opportunities involve tradeoffs (for example, between the cost of developing a new machine with increased capability and buying two off-the-shelf machines and incurring extra setups). The PFC should not fund projects using these concepts unless the specific benefits make sense under a reasonable range of expected production conditions.

The other PFC technical areas – process modeling and sensor-based control – also promote flexibility. Process modeling deals with the ability to correlate process inputs with process results. This reduces first-part cost and is critical to small-batch production. Sensor-based control deals with the use of machine-based sensors for in-process monitoring. Such monitoring helps cope with the

[2]The Association for Manufacturing Technology, *A Research Agenda for the Machine Tool Industry* (Draft Report), March 1992, p. 17.

[3]Ibid., p. 5.

uncertainties present in all processes and is also vital to small-batch production. Although these topics are addressed later in this report, we mention them here to emphasis their importance in supporting flexible manufacturing.

Benefits

The approaches outlined above fill the need for less expensive tooling, more rapid setup techniques, and more capable equipment in precision fabrication processes. Economical batch size is proportional to the ratio of fixed setup costs to run costs. Fixed costs include tools and fixtures as well as the time to set up. Today, many companies are cutting batch sizes and hoping they can then reduce setup costs. They are willing to pay a premium for faster throughput, but the added cost is nevertheless present and either comes out of profit or is passed on to the customer. Expanding the capability of individual processes means that a factory can reduce the number of types of equipment that it maintains, along with the associated support costs. Scheduling becomes easier, and machine utilization rises, lowering total capital equipment costs. Finally, developing equipment that performs multiple functions decreases the number of process steps a workpiece must undergo and thereby cuts the time and distance a part travels before leaving the factory.

These technologies can not only shift the historic cost/quantity relationship of recurring production but can also speed product development. If small lots can be made economically and quickly, prototype products can be built on the same lines with production units. This would provide designers with important feedback on production issues.

A PFC focus on flexible manufacturing could be an important source of new technology for DoD's organic manufacturing facilities – the depots and arsenals. DoD's Flexible Computer Integrated Manufacturing (FCIM) program addresses primarily data representation and exchange between users, engineering, and manufacturing sites. The reduction of shop-floor lead time is a goal of FCIM, but the focus is now on the nontechnical aspects discussed above. The development of flexible processing technologies by the MS&T Program would enhance FCIM's current efforts.

Process Modeling

Description

The process modeling technical area covers studies, tools, and techniques that improve the understanding of the physics and chemistry of precision processes. The scope includes both process-specific modeling done in advance of production (for example, to establish process instructions) and the capture and feedback of production experience into process data bases. At a major jet engine producer, for example, castings and forgings from suppliers typically proceed through 30 to 50 fabrication steps before being ready for assembly. Each of these operations alters the physical features of the part – geometric, mechanical, etc. – on the basis of a set of process parameters. Manufacturing engineers define many process parameters explicitly in the operation instructions; others are implicitly defined by the factory environment. Explicit process parameters for a drill, mill, or turning operation might include the following:

- The workpiece's nominal material properties
- The machine feed, speed, and depth of cut (of which there might be several, for rough and finish cuts)
- The workholding device (contact points, rotational symmetry, rigidity)
- The cutting tool material and geometry
- The coolant material and delivery system
- The chip removal technique.

Implicit process parameters that might affect this operation include the following:

- The time variation of factory temperature
- The relative humidity
- Material properties induced by previous operations (e.g., local surface hardening)
- Shop-floor vibration.

The aim of process modeling is the ability to correlate process inputs with process results. Three broad challenges face process modelers. The first is to understand how changes in a given parameter affect process outcome when all other parameters are held constant. The second is to understand how the parameters affect each other. For example, workholding and cutting tool configuration affect how a workpiece can be cooled. Experimental approaches, such as "Taguchi methods," exist to guide engineers through these first two challenges. Once these relationships are understood, process engineers can develop techniques that optimize processes to desired levels of precision and throughput. For example, taps are now being marketed that deliver coolant through the shank, improving both coolant delivery and chip removal. The third challenge is to take these learned relationships and extrapolate from them into new ranges. This is the challenge posed when a new material is developed, when a new product is designed, or when the operating range of a piece of equipment is expanded.

Process modeling is not a new concept. Material and process data bases for many materials – such as commonly used steels and aluminums – have been compiled and published (sources include, for example, ASM International, the American Society of Mechanical Engineering, and the Institute of Advanced Manufacturing Sciences). Despite the availability of experimental approaches, however, process modeling is too often supplanted by trial-and-error learning. In addition, the same learning is done – and the same problems are solved – over and over, both within a given factory and by different companies. While a certain level of such replication is a necessary byproduct of competitive industries developing proprietary processes, such efforts are unaffordable and unnecessary under Government-funded projects.

Goals

Today's manufacturing environment places new demands for better process understanding. The call for speed and quality, a revolution in new materials (led by polymer-, metal-, and ceramic-matrix composites), the capability for computer control and feedback, and ever-improving computer simulation tools make process modeling both a needed technology and one ripe for improvement. The PFC should promote two goals for process modeling:

- Expand the scientific basis for defining precision fabrication process parameters
- Foster and expand the use of data bases (including both "hard" data and expert rules) containing process relationships.

Accordingly, MS&T attention should be directed at the following:

- Developing computer simulations for predicting process behavior that is not well understood or process parameter values that are outside the realm of experience
- Speeding the validation and compilation of experimental process results into data bases
- Providing the level of information needed for automated planning and control
- Updating data on materials whose process behavior is well known to reflect advances in process capability.

MS&T should give priority to modeling the processing of materials that are new or that are currently unique to DoD (many of which have potential commercial application) and for which process data are immature. This would include well-known materials whose "process envelopes" are being expanded by advances in fabrication technology. An example of such a process is the cutting of 6061-T6 aluminum plate for a missile guidance assembly, the time for which was recently reduced from 17 hours to just over one hour by high-speed machining. "The biggest obstacle to high-speed machining is overcoming its myths and misconceptions.... As manufacturing engineers learn more about appropriate work materials and technologies, however, more firms will benefit from shorter production times, better part quality, and better part costs."[4]

Benefits

Process modeling will yield benefits in product development as well as in recurring production. In product development, process modeling contributes to rapid prototyping and producibility planning. Reliance on specialty labs to build initial units should diminish. Although "rapid prototypes" built by processes like stereolithography are currently in vogue (and will continue to perform an important function), these processes typically yield parts that can be evaluated for form and fit, but not for function. Process modeling can help meet the need to speed the production of full-feature prototypes for early-as-possible operational testing. Process models are also useful tools for producibility assessment. Reliable process models can provide a consistent and accurate tool for evaluating the production implications (tooling requirements, run time, yield, etc.) of a contemplated design.

In recurring production, process modeling reduces learning time, enhances adaptive control, and supports multiple sourcing. The main purpose of process modeling is to support "one start, one part" production. Unambiguous product and process descriptions will mean that operator learning should occur faster. Workers will need to run fewer pieces (optimally only one) to get the "feel" of a process and to turn out good quality parts. Process modeling improves adaptive control by helping engineers identify which data elements are most important to monitor and how often they must be checked. When anomalies are detected, the models can also be used to provide logic suggesting corrective actions. In this sense, process modeling is a complement to the sensor-based control technical area, discussed below. Finally, process models can be archived and distributed. These data bases can reduce the effort in starting multiple production sources, as in the case of surge or mobilization.

SENSOR-BASED CONTROL

Description

Sensor-based control is the technical area dedicated to monitoring, sensing, measuring, and otherwise detecting process conditions and feeding those condi-

[4]John R. Coleman, "No-Myth High-Speed Machining," *Manufacturing Engineering* (Dearborn, Mich.: The Society of Manufacturing Engineers, October 1992), p. 61.

tions back to machine controllers. Types of process conditions that can be monitored by sensors include:

- Workpiece condition (e.g., geometry, strain, heat profile)
- Tool condition (e.g., wear, breakage)
- Workholding condition (e.g., offset, alignment, rigidity)
- Equipment condition (e.g., vibration, power consumption, bearing temperature).

These conditions can be continuously changing (or nearly so, as in material removal), or they can be discrete events (such as tool failure). Frequently, one measurand gives information about other factors. For example, an increase in a lathe's power consumption may indicate worn bearings. Detecting and acting on this condition can prevent costly spindle damage and associated machine downtime. Sensors can detect these conditions over a wider bandwidth (e.g., over the electromagnetic spectrum) and with greater resolution in time and space than can humans.

The purpose of sensor-based control, then, is to detect and automatically compensate for changes that affect a process's precision. The following examples of metal turning process conditions illustrate the opportunity for sensor-based control:

- A loading dock door near a turning center is opened in winter. The air temperature around the machine drops 10 degrees during a boring operation. The workpiece shrinks, causing the tool to overcut. The part is ruined.
- The coolant spray wanders off of the workpiece during a prolonged cutting operation. The workpiece overheats, destroying itself and the tool.
- A magazine-fed lathe is running a finishing operation on 1000 parts, each requiring an interrupted cut taking one minute. The tool wears prematurely and starts chattering. The operator, tending another machine, doesn't notice for five minutes. Four parts must be sent to the grinding department for rework.

Sensor-based control also offers the opportunity to capture shop-floor experience and enter it in engineering data bases more consistently than is possible with ad hoc approaches. For example, is excessive tool wear an isolated problem due to hard spots in the workpiece, or is it a chronic problem due to improper operation instructions? Questions such as this arise every day at every factory workstation, and usually they are "solved" on the spot by the operator. Rarely are they tracked — the amount of data requires electronic collection, reduction, and storage — and patterns emerge only when the operator notices them.

Traditional approaches to process control rely on machine settings, such as stops and switches, and on in-process inspection using hand tools and gages. On semi-automatic machines, operators frequently revert to manual control for the final cut or pass in a cycle. Because of tool wear, and even machine wear, processes drift and operators often mistrust machine settings. As a result, they frequently interrupt process cycles to inspect the workpiece. While this in-process inspection may take place at the machine, it often requires a unload/load action (for example, when a ring gage must be placed over a part held between centers).

In-process inspection is particularly challenging for contoured parts, such as turbine engine airfoils. Such "shaped" parts historically have been measured at a few points using commonly available tools such as dial indicators and calipers. In cases where net shape has a strong effect on performance, specialized tooling (guillotine gages in the airfoil case) is developed that precisely conforms to specific locations on the part. Departures from correct shape are sensed with feeler gages or by looking for light leaking through gaps between the "perfect" master and the measured part. In some cases, surfaces are even measured by eye to determine if the surface is "fair."

These traditional approaches to process control are slow, lack precision, and require large fixed costs (in the case of master gages). Each blade type in a turbine, for example, requires at least $50,000 in gages and fixtures. For one plant producing 500 blade types, this means a $25 million investment. In recent years, devices have come on the market that reduce the need for specialized gaging. These typically employ contact probes sensing pressure and displacement. The most popular is the coordinate measuring machine (CMM), a stand-alone device that probes a part in three dimensions and can digitize the results for comparison against a computerized part representation. Contact probes, however, are limited by the types of conditions that they can monitor and by the spaces into which they can reach. CMMs in particular are limited by their work envelope, their need to be isolated from vibration and changes in temperature, week-long calibration cycles, and their relatively slow throughput.

The drive toward collecting more process data, for increasing throughput, and for minimizing "hard" gaging puts pressure on manufacturing engineers to employ alternative approaches to process control and inspection. Non-contact sensors are now emerging as mature technologies ready for development into shop-floor systems. Non-contact sensors may be used to draw inferences about workpiece conditions based on the following media:

- Visual (portion of the electromagnetic spectrum)
- Infrared
- X-ray
- Magnetic field

- Acoustic
- Chemical (air composition).[5,6]

Visual and x-ray techniques are usually active, utilizing a signal generator to bounce signals off the target part onto a detector. Infrared, magnetic, acoustic, and chemical techniques are usually passive, relying on the part or machine to generate some signal that is picked up by a detector. Laser sensors typically operate in either the visual or the infrared bands.

Non-contact sensors are being developed to monitor the workpiece, workholding, tool, and equipment conditions described above. Frequently, these sensors are derived from those originally developed for military weapon systems. The challenge is adapting the sensor to the distances, geometries, and integration times of the factory, which differ significantly from those encountered by weapons in the field. One example is laser radar for range sensing. When used as an aircraft altimeter, laser radar requires a depth of field of kilometers against relatively flat surfaces. Updates on the order of seconds are adequate. In contrast, when used to measure a workpiece, the sensor requires much lower depths of field but against targets whose surface can vary suddenly. For in-process control, updates on the order of milli- or micro-seconds are necessary.

Goals

The PFC should support the development and commercialization of process sensors that can be integrated with machines, machine controllers, and manufacturing engineering data bases. The goals for these devices would be to:

- Reduce process variability through sensory information, feedback loops, and appropriate control algorithms
- By performing in-place inspection, eliminate the need to unload/reload the workpiece for measurement
- Eliminate scrap due to excess material removal
- Reduce the need to interrupt the machine cycle to perform inspection
- Track process condition data and feed the data to process improvement activities.

When it makes sense to do so, the PFC should seek the manufacturing application of sensing technologies that have been developed for weapon systems (at Government expense) and encourage the commercialization of sensors that have

[5] Paula M. Noaker, "Sensible Sensing for Assembly," *Manufacturing Engineering* (Dearborn, Mich.: The Society of Manufacturing Engineers, September 1992), p. 52.

[6] Keith Brindley, *Sensors and Transducers* (London: Heinemann Professional Publishing, 1988), p. 14.

been developed with Government funds but whose technical data are company proprietary.

Benefits

Fast, accurate in-process measurement without special gaging could save U.S. industry millions of dollars per plant. Sensor-based control complements the process modeling technical area by providing the means to collect shop process data electronically and automatically. Machines capable of digitizing shape can provide the data to computer-aided manufacturing systems for comparisons with product and process models, which will result in greatly accelerated process corrections. Noncontact sensing can provide great improvements in throughput by eliminating collision and dynamics issues associated with mechanical contact approaches to process control. Also, by reducing operator intervention for piece-part inspection, sensor-based control can increase throughput (particularly where a single operator is running multiple machines in a work cell). Although in-process time is not generally a large component of manufacturing cost, a decrease in the flow time of bottleneck operations would contribute to industrial responsiveness.

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APPENDIX A

Progress Since the 1991 Plan

This appendix summarizes the history of the Precision Fabrication Committee and discusses implementation of the previous plan, prepared in 1991. Continued prospects for lower defense procurements, defense industry restructuring (mergers, plant closings, etc.), and technical lessons learned all suggested that a revision to the 1991 plan was necessary.

The Precision Fabrication Committee came to the MS&T program in late 1992 when the Manufacturing Technology (ManTech) program was transferred from the Assistant Secretary of Defense (Production and Logistics) to the Director of Defense Research and Engineering. In 1991, the committee was called the Precision Machining and Forming Committee. Prior to 1991, the group was known as the Metals Committee of the Manufacturing Technology Advisory Group.

In 1991 the committee issued a strategic plan establishing four technical areas for improving the accuracy, repeatability, resolution, flexibility, and productivity of machining and forming processes. The committee recommended spending $72 million between FY92 and FY95 on the following:

- Next-generation and low-end machine controllers ($26 million)
- Sensor-based systems ($13 million)
- Machine modules ($8 million)
- New processes for advanced materials ($25 million).

The machine controller area sought a common look and feel, a common operating system, and a common application interface for controllers from different manufacturers. These capabilities would permit factories to create in-house integrated systems. In the area of sensor-based systems, there would be an attempt to integrate on-machine sensors with controllers to provide setup assistance, in-process measurement, closed-loop process control, and warning of catastrophic tool failure. The machine modules area would develop machine drive, work-retention, and work-changing components to take the increased mechanical and thermal loads of high-speed machining. These components would be designed to take advantage of the controller and sensor capabilities described above. Finally, the new processes area sought improvements to the machining of metals (in areas such as laser processing and tool life extension) and to the machining of ceramics and composites.

The flow of funding to these technical areas, in total, has matched the recommendations. Assuming that the 1991 planning committee intended that one-quarter of its total recommendation would be spent in each of the four planning years, one half of the total amount should have been allocated from FY92 to FY93. With the planning period half over, $37 million of the recommended total of the recommended $72 million has been awarded to projects. The mix of allocation to each technical area, however, has varied from that recommended. Figure A-1 shows the total amount recommended, the expected allocation to date (which equals the total amount for four years, divided by two), and the amount awarded to date for each technical area in the 1991 plan. While funding for advanced controllers is about on target, funding for sensor-based systems and machine modules is lagging. There apparently has been a re-allocation of funds away from these areas to advanced materials and processes, which is running ahead of recommended funding.

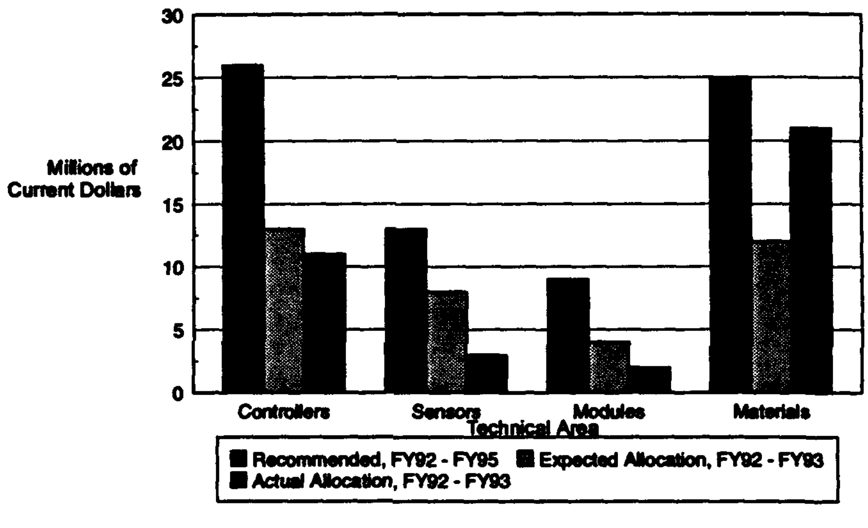


Figure A-1.
Comparison of Funding Recommended in the 1991 Plan with Expected and Actual Results

Advanced controllers have received $11 million of the $26 million recommended in 1991. Table A-1 shows the two advanced machine controller projects that have been started or that have received additional funding since the 1991 plan. The Air Force's Next Generation Workstation/Machine Controller project (already in existence when the FY91 report was prepared) has received $10 million since FY91. The Navy's Advanced Machine Tool Controllers project, hoping to draw on the NGC results, has received about $1 million.

About $3 million of the recommended $13 million has been awarded to sensor-based systems projects (see Table A-2). The approximate split by Service is Air Force, $1.6 million; Army, $0.7 million; and Navy, $0.7 million.

Table A-1.
Next-Generation and Low-End Machine Controller Projects Resulting from the 1991 Plan

Project Title	Sponsoring Agency
Next Generation Workstation/Machine Controller	Air Force
Advanced Machine Tool Controllers	Navy/NIST

Table A-2.
Projects Dedicated to Sensor-Based Systems

Project Title	Sponsoring Agency
Dimensional and Surface Profile Measurement	Air Force
Dimensional Gauging of Engine Components	Army
Manufacturing Technology for Cutting Performance of Machining Centers	Air Force
Non-Contact Laser Profile Gage	Air Force
Plasma Spray Sensor Development	Navy
Real-Time Tool Condition Monitoring	Air Force
Sensory Feedback in Adaptive Machining	Navy
Spindle Thermal Error Compensation	Air Force
Tri-Beam Gage for Turning Centers	Air Force
Ultrasonic Sensors	Navy
Ultrasonic Tube Wall Thickness	Army

In addition, several other projects incorporate sensor-related R&D into broader efforts. These projects are listed in Table A-3.

Table A-3.
Other Projects Incorporating Process Sensing R&D

Project Title	Sponsoring Agency
Application of Neural Nets in Motion Control	Navy
Chemical Vapor Infiltration of Ceramic Matrix Composites	Air Force
Increasing Machine Precision	Navy
OPTICAM for Spherical Grinding and Finishing	Army

About $2 million of the $8 million recommended for developing machine modules has been allocated.[1] In FY91, the Air Force transferred $1.5 million to NIST for work in high-speed spindles and thermal error compensation.[2] In FY93, the Navy allocated $110,000 for "Precision Electro-mechanical Actuators." This project deals with actuators in servo systems for single-point turning of complex geometries. A Navy/NIST project entitled "Advanced Machine Tool Structures" was allocated $425,000 in FY93 and is slated to receive an additional $1.75 million in the future. NIST will develop a metrology system for a prototype multi-axis machining center to be built by a private company.

The final technical area specified in the 1991 plan is "new processes for advanced materials." While this technical area could include almost any process/material-specific project (and was no doubt deliberately worded to provide flexibility in program implementation), the plan does identify several categories needing attention. These are listed in Table A-4.

Table A-4.
"New Processes for Advanced Materials" Identified in the 1991 Plan

New Processes for Advanced Materials
Laser processing (cutting, welding, and drilling)
Electro-chemical milling
Gear machining
High-speed threading
Tool life improvement
Thin-section casting

While not all of the improvements in Table A-4 have been pursued, this technical area has had the most comprehensive implementation of all in the 1991 plan. Of the $25 million recommended, over $21 million has been allocated. Table A-5 shows projects that have been started since (and presumably because of) the FY91 plan. Funding allocated to these projects through FY93 totals $10.7 million.

Table A-6 lists additional projects that were already underway at the time of the 1991 plan and are continuing today. Funding for these projects in FY92 and FY93 exceeds $10 million.[3]

[1] Prior to the FY 91 plan, the Air Force conducted an initiative entitled "Machine Tool Products and Processes," comprising nine projects. Each of the projects in that initiative was started prior to the 1991 plan.

[2] Interview with Air Force ManTech personnel, 19 April 1993.

[3] For some of the projects, we were not able to distinguish FY92 funding from prior years' funding.

Table A-5.
Projects in New Processes for Advanced Materials Resulting from the 1991 Plan

Project Title	Sponsoring Agency
Casting of XD Intermetallic Matrix Composites	Navy
Chemical Vapor Infiltration of Ceramic Matrix Composites	Air Force
Coatings Producibility	Air Force
Improved Broaching of UDIMET 720	Army
Linear Friction Welding	Navy
Materials Standards for Powdered Metal Alloys	Navy
Metal Matrix Composites	Air Force
Metal Matrix Composites Program	Navy
Precision Machining of Advanced Materials	Navy
Thin Wall Castings	Air Force

Table A-6.
Currently Active Advanced Materials and Processing Projects Begun Prior to the 1991 Plan

Project Title	Sponsoring Agency
Advanced Consumables for Welding 80 – 100 ksi Strength Steels	Navy
Electroslag Surfacing Technology	Navy
Laser Corrosion Cladding	Navy
Laser Materials Processing	Navy
Powder Injection Molding	Navy
Powder Metallurgy Initiative	Navy
Premium Quality Titanium Alloy Disks	Air Force
Spray Metal Forming	Navy
Thermomechanical Processing of Gears	Navy
Titanium Aluminide and Titanium Alloy Foil	Air Force
Titanium Aluminide Composite Engine Structures	Air Force
Titanium Matrix Composite Initiative: Engine Components	Air Force
Titanium Matrix Composite Initiative: Exhaust Nozzle Components	Air Force
Titanium Matrix Composite Initiative: Mode Strut	Air Force
Titanium Matrix Composite Initiative: Ring Inserts	Air Force
Titanium-Aluminide XD Composite	Navy
Tungsten Alloy Penetrators	Navy

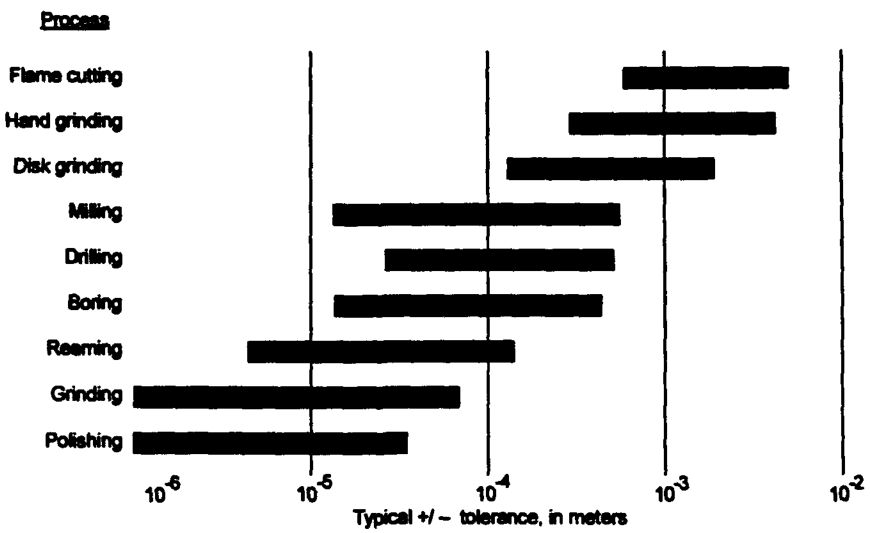
APPENDIX B

Why "Precision"

In this appendix we discuss the meaning of the term "precision" and why precision fabrication is of central importance to providing our armed forces with first-rate equipment.

ASPECTS OF PRECISION

"Precise" means "capable of, resulting from, or designating an action, performance, or process executed or successively repeated within close specified limits." "Precision" means "made so as to vary minimally from a set standard."[1] The notion of precision is relative to the scale and type of product being fabricated. Precision, when referring to the overall length of a large ship, for example, is measured on the order of centimeters. Precision, when referring to the surface of a mirror, is measured on the order of microns. Precision also varies by process. Figure B-1 shows typical tolerances for some material removal processes.



Source: Adapted from Cubberly, William H. and Ramon Bakerjian, eds. *Tools and Manufacturing Engineer's Handbook.* Dearborn, Mich., Society of Manufacturing Engineers, 1989, p. 8-2.

Figure B-1.
Typical Tolerances for Material Removal Processes

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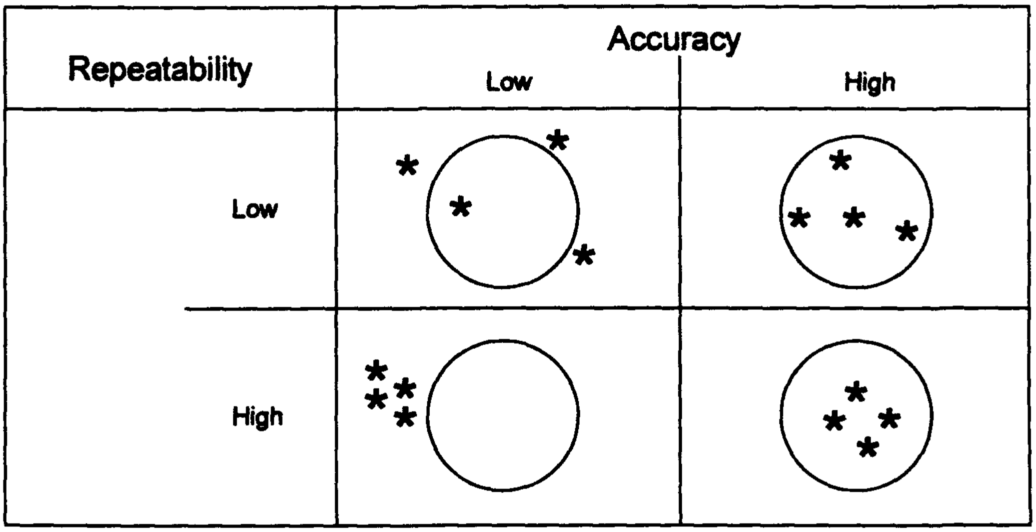
[1] *The American Heritage Dictionary* (Boston: Houghton Mifflin Company, 1985), p. 975.

Three terms collectively describe precision in manufacturing: resolution, accuracy, and repeatability.[2] Resolution is the minimum difference in value that can be distinguished by a sensor, such as the human eye or a scale. For example, the human eye can theoretically distinguish from a distance of 400 meters two point sources (such as candles) of light that are 4 centimeters apart.[3] Beyond this range, the two sources appear as one. Accuracy is a measurement's closeness to a desired value. Repeatability is the relative ability of a process to produce consistent results over time. Figure B-2 illustrates the difference between accuracy and repeatability.



Source: Adapted from Cubberly, William H. and Ramon Bakerjian, eds. *Tools and Manufacturing Engineer's Handbook*. Dearborn, Mich., Society of Manufacturing Engineers, 1989, p. 8-2.

Figure B-2.
Accuracy vs. Repeatability (where the area inside the circle represents the target)

The PFC seeks technologies that will increase the resolution of the processes described above and that will make them more accurate and repeatable. As will be discussed, these aspects of precision apply primarily to physical properties of the material being fabricated and the machinery being used. The PFC also seeks technologies that will make these processes more affordable and responsive to customer demand, within established bounds of precision.

[2]This discussion is adapted from William H. Cubberly and Ramon Bakerjian, eds., *Tool and Manufacturing Engineer's Handbook* (Dearborn, Mich.: Society of Manufacturing Engineers, 1989), pp. 12-1, 12-2.

[3]John David Vincent, *Fundamentals of Infrared Detector Operation and Testing* (New York: John Wiley and Sons, 1990), p. 396.

HOW PRECISION FABRICATION INFLUENCES PERFORMANCE, COST, AND SCHEDULE

Precision fabrication processes influence life-cycle schedule, cost, and performance through *physical factors* and *operational factors*. Physical factors are those characteristics of the workpiece (the material being transformed) that are defined explicitly by performance requirements (for example, a turbine blade's operating temperature) or implicitly by design engineers (for example, through the selection of one material over another). Operational factors are those characteristics of the factory that influence the quantity and effectiveness of labor and machinery needed to meet production requirements.

Physical Factors

The main physical factors influenced by precision fabrication processes are geometric and mechanical properties (see Table B-1). Geometry includes all manner of dimensional measures: linear measurement, straightness, flatness, roundness, angularity, parallelism, and others. Mechanical properties include strength, hardness, and ductility. Other physical factors frequently associated with weapon system components – but little affected by precision fabrication processes – include electrical, chemical, and thermal properties. These other properties are determined more by the materials themselves than by the processes that transform them.

Table B-1.
Impact of Selected Precision Fabrication Processes on Physical Properties of Items Being Produced (no entry means low impact)

Process	Physical Properties				
	Geometric	Mechanical	Electrical	Chemical	Thermal
Casting	High	High			
Forging	High				
Machining	High				
Grinding	High				
Heat Treat	Medium	High	Medium	Medium	
Welding	High	High			

Most precision fabrication processes obviously have a high impact on workpiece geometry, since their main purpose is to alter the shape of materials. Heat treatment has a moderate impact on geometry because, while its main purpose is to alter the material microstructure, it can shrink the workpiece. Casting, heat treating, and welding also have a high impact on mechanical properties. Porosity in castings, for example, causes structural weakness and poor appearance.

Forging and machining have a low impact on mechanical properties because while in some cases they induce microstructure changes in the workpiece, these changes are generally unintentional and unwanted. Annealing, a form of heat treatment, can alter the electrical or magnetic properties of a metal.[4] Improper annealing of stainless steel will permit chromium (the rust-inhibiting element) to bond with carbon rather than with iron, making the stainless steel vulnerable to oxide corrosion.[5]

Operational Factors

Time, quality, and product demand are interrelated operational factors that affect, and are affected by, precision fabrication processes. In manufacturing today, time is considered the most important competitive factor. Companies are increasingly measuring their operations, from fielding products to processing paychecks, by the time required. Activities that take a long time hide inefficiencies and cause loss of opportunities. Several activities that consume time particularly relevant to precision fabrication processes are shown in Table B-2; they are found in all precision fabrication processes. Other time-consuming activities include searching for parts and tools, and idle time. These and related issues of manufacturing scheduling, logistics, and administrative support fall within the realm of the manufacturing systems sub-thrust.

Table B-2.
Precision Fabrication Activities Whose Times Contribute Significantly to Manufacturing Competitiveness

Activity (time consumer)	Description	Impact
Setup	Time to prepare a machine to run a given part; includes any configuration changeover and post-run teardown.	A semi-fixed cost incurred every time a batch of parts is run, whether the batch size is 1 or 10,000. Major factor in economic lot size calculation that determines inventory levels.
Run	Process time per part, including load and unload.	Limits throughput of equipment, thereby determining number of machines required to produce a given volume of product.
Inspection	Time to check conformance with specifications. May be included in run time or in addition to it (or both).	Increases process cost not only by actual inspection time, but frequently by additional machine loads and unloads. May idle machinery and operators who must wait for inspectors.
Machine maintenance and repair	Downtime when a machine cannot be set up or run.	Reduces the number of machines effectively available, increasing the number required to produce a given

[4] Cubberly and Bakerjian, p. 41-11.

[5] Donald R. Askeland, *The Science and Engineering of Materials* (Boston: PWS-KENT Publishing Company, 1989), p. 799.

Poor quality continues to be a major contributor to the cost of manufactured products. For purposes of the PFC, quality refers to the adherence of a product's physical properties to design specifications at each stage of production. A factory can ship perfect products and still have poor quality. Quality affects the cost of shop-floor labor, above-the-shop-floor support, and operating costs. The cost of quality is reflected in the amount of scrap and rework generated, in the amount of inspection required to weed out bad products, and in material review boards that ponder whether to accept marginal products. Mated parts that are at opposite ends of their respective tolerance bands (that is, one at the high end and one at the low end) may wear excessively in the field, increasing operating costs.

"The nature of demand" is an operational factor that plays a large but often neglected role in configuring manufacturing processes; it refers to the mix of products being made on a given manufacturing line and the magnitude and variability over time of demand for those products. Different demand patterns require different approaches to fabrication. Conversely, the production capabilities of a given process (for example, turning) determine and limit the types of product demand that can be economically serviced by that process. The production of hand drill rotor shafts with high, predictable volume may be best accomplished by a multiple-spindle automatic screw machine. The production of custom-designed actuator shafts for spacecraft may be best accomplished on a single-spindle CNC turning center. Within some limitations, existing machinery and tooling can be reconfigured to accommodate economically different product volumes and mixes. The match between equipment capability and the nature of demand should be a major factor in machinery development and purchasing.

These operational factors – time, quality, and the nature of demand – often interact. Rework increases run time and throughput time, increasing labor, equipment, and inventory costs. Long setups limit the ability of a process to produce economically in small lots. Good quality that is achieved by intensive inspection comes at the expense of longer throughput time.

APPENDIX C

MS&T Precision Fabrication Projects

The attached list shows MS&T precision fabrication projects that were active as of September 1993. The data are stored in a Microsoft Access data base and were compiled from Army, Navy, and Air Force project books as well as from various individuals within DoD. The primary source for each project's information is listed.

Title:	Chemical Vapor Infiltration of Ceramic Matrix Composites
Performing Agency:	Air Force
Status:	Funded
Description:	ManScience program. Develop CMCs and the associated manufacturing processes to meet Integrated High Performance Turbine Engine requirements. Develop process sensors to collect and feed forward data to process controllers. Monitor process in real time, obtimize fiber architecture, and implement model-based control.
Funding: ($000)	**Total Estimated Cost:** $3,600

Prior Investment	FY93	FY94	FY95	Cost to Complete
$200	$0	$1,000	$0	$2,400

Milestones:	Est. 7/93 Start. No Completion date determined.
Reference:	1992 Project Book, p. 105

Title:	Coatings Producibility
Performing Agency:	Air Force
Status:	Funded
Description:	Develop coating application techniques and process control for an advanced oxidation-resistant material developed under a previous ManTech effort. Apply to the F-199 engine.
Funding: ($000)	**Total Estimated Cost:** $3,500

Prior Investment	FY93	FY94	FY95	Cost to Complete
$300	$100	$1,000	$0	$2,100

Milestones:	
Reference:	Schulz fax, 10/29/92

Title:	Ductile Iron
Performing Agency:	Air Force
Status:	Funded
Description:	Establish a computer model that assists the engineer in designing molds and patterns used to cast ductile iron. Include green sand, lost foam, and no-bake mold processes. Congressionally directed.
Funding: ($000)	**Total Estimated Cost:** $2,000

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$2,000	$0	$0	$0

Milestones:	
Reference:	Schulz fax, 10/29/92

Title:	Flexible Automated Welding for Blade Tip Repair
Performing Agency:	Air Force
Status:	Funded
Description:	RepTech program. Develop semi-automatic or automatic processes for repair of single crystal and directionally solidified turbine engine blade tips.
Funding: ($000)	**Total Estimated Cost:** $4,450

Prior Investment	FY93	FY94	FY95	Cost to Complete
$200	$100	$1,100	$0	$3,050

Milestones:	Est. 4/93 Start. 12/96 Completion. Develop a Flexible Automated Welding Machine (FAWM). Establish an automated blade tip repair cell using the FAWM. Implement the cell at the Oklahoma City ALC. Reduce scrap by 30 percent.
Reference:	1992 Project Book, p. 204

Precision Fabrication Projects

Title:	Machine Tool Sensors: Dimensional & Surface Profile Measurement
Performing Agency:	Air Force
Status:	Funded
Description:	Develop a capacitative non-contact analog probe and a capacitative array dimensional measurement system to check the dimensions of compex shapes.
Funding: ($000)	**Total Estimated Cost:** $300

Prior Investment	FY93	FY94	FY95	Cost to Complete
$300	$0	$0	$0	$0

Milestones:	3/91 Start. 7/93 Completion. Demonstrate on a plasma-arc turning center.
Reference:	1992 Project Book, p. 141

Title:	Machine Tool Sensors: Tri-Beam Gage for Turning Centers
Performing Agency:	Air Force
Status:	Funded
Description:	Develop an optical "v-block" gage for measuring diameter of turned parts on-machine and in-process.
Funding: ($000)	**Total Estimated Cost:** $300

Prior Investment	FY93	FY94	FY95	Cost to Complete
$300	$0	$0	$0	$0

Milestones:	3/91 Start. 6/93 Completion.
Reference:	1992 Project Book, p. 139

Precision Fabrication Projects

Title:	Metal Forming Simulation
Performing Agency:	Air Force
Status:	Funded
Description:	RepTech program. Establish a 3-D CAD/CAM/CAE system to simulate the Guerin (rubber-pad) sheet metal forming process. Apply to operations at Air Logistics Centers.
Funding: ($000)	**Total Estimated Cost:** $2,300

Prior Investment	FY93	FY94	FY95	Cost to Complete
$150	$250	$600	$0	$1,300

Milestones:
Est 2/93 Start. 6/96 Completion.
Phase I: Define system requirements.
Phase II: Develop analytical model.
Phase III: Demonstrate system at Warner-Robins ALC.

Reference: 1992 Project Book, p. 198

Title:	Metal Matrix Composites
Performing Agency:	Air Force
Status:	Funded
Description:	Establish processes to reduce the cost of manufacturing Ti matrix composites by at least 50 percent via cycle time reduction, low-cost tooling, and efficient inspection. (Congressionally directed)
Funding: ($000)	**Total Estimated Cost:** $20,610

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$5,000	$0	$0	$15,610

Milestones:

Reference: Schulz fax, 10/29/92

Precision Fabrication Projects

Title: National Center for Manufacturing Science

Performing Agency: Air Force

Status: Funded

Description: Congressionally-directed grant.

Funding: ($000)

Total Estimated Cost: $45,000

Prior Investment	FY93	FY94	FY95	Cost to Complete
	$45,000	$0	$0	$0

Milestones:

Reference: 1992 Project Book, p. 136

Title: Premium Quality Titanium Alloy Disks

Performing Agency: Air Force

Status: Funded

Description: Establish new processes for preparation of Ti alloys for gas turbine engine compressor disks. Minimize Type I and Type II defects and high density inclusions. Emphasize process cleanliness and nondestructive test equipment.

Funding: ($000)

Total Estimated Cost: $4,196

Prior Investment	FY93	FY94	FY95	Cost to Complete
$3,049	$1,100	$47	$0	$0

Milestones:
9/89 Start. 6/94 Completion.
Phase I: pilot-scale demonstration.
Phase II: scale-up to commercial practice levels.

Reference: 1992 Project Book, p. 124

Title:	Reactive Fragment Warhead Program
Performing Agency:	Air Force
Status:	Funded
Description:	Establish a low-cost, high-volume production capability for reactive fragment air-to-air missile warheads.
Funding: ($000)	**Total Estimated Cost:** $5,200

Prior Investment	FY93	FY94	FY95	Cost to Complete
$300	$200	$1,750	$0	$2,950

Milestones:
New Start. Est. 5/93 Start. 6/96 Completion.
Phase I: Establish new process design.
Phase II: Fabricate production hardware and validate process.
Phase III: Demonstrate capability to produce 50,000 filled fragments per month at a production cost of less than $10 per unit. Baseline capability is 200 units per month at a unit cost of $650.

Reference: 1992 Project Book, p. 154

Title:	Thin Wall Castings
Performing Agency:	Air Force
Status:	Funded
Description:	Develop the capability to manufacture thin, light weight nickel exhaust nozzle liners. Also, develop a porous coating/cooling system for thin liners.
Funding: ($000)	**Total Estimated Cost:** $2,000

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$100	$500	$0	$1,400

Milestones:

Reference: Schulz fax, 10/29/92

Title: Titanium Aluminide and Titanium Alloy Foil

Performing Agency: Air Force **Status:** Funded

Description: Reduce the cost and lead time, and increase the quality and yield, of TiAl and Ti alloy foil used in continuous fiber (SiC) metal matrix composites. Applications include aircraft and missile structures and engine components.

Funding: ($000) **Total Estimated Cost:** $2,700

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,749	$0	$480	$0	$951

Milestones:
9/91 Start. 1/95 Completion.
Phase I: Develop plasma spray preform.
Phase II: Production of 14-inch wide near-alpha and alpha-2 TiAl preforms
Phase III: Production of 26-inch wide alpha-2 TiAl preforms

Reference: 1992 Project Book, p. 144

Title: Titanium Aluminide Composite Engine Structures

Performing Agency: Air Force **Status:** Funded

Description: ManScience program. Evaluate alternative fabrication techniques, including foil-fiber-foil, plasma spray, tape casting, cold spray, and physical vapor deposition. Expand process understanding for the most promising processes.

Funding: ($000) **Total Estimated Cost:** $4,710

Prior Investment	FY93	FY94	FY95	Cost to Complete
$2,560	$0	$2,000	$0	$150

Milestones:
9/91 Start. 1/95 Completion.
Phase I: Assess fabrication alternatives and identify producibility gaps.
Phase II: Establish scientific basis for processes through controlled experiments.
Phase III: Demonstrate production of turbine engine components leading to 200C increase in compressor temperature and reducing compressor weight by 50 percent.

Reference: 1992 Project Book, p. 112

Title:	Titanium Matrix Composite Initiative: Engine Components
Performing Agency:	Air Force
Status:	Funded
Description:	Establish process controls and non-destructive inspection techniques. Demonstrate on gas turbine engine exhaust nozzle links.
Funding: ($000)	**Total Estimated Cost:** $9,515

Prior Investment	FY93	FY94	FY95	Cost to Complete
$9,515	$0	$0	$0	$0

Milestones:	9/91 Start. 2/95 Completion. Reduce cost of Ti-matrix composite engine parts by 50 percent from 1991 to 1995.
Reference:	1992 Project Book, p. 128

Title:	Titanium Matrix Composite Initiative: Exhaust Nozzle Components
Performing Agency:	Air Force
Status:	Funded
Description:	Optimize producibility, improve quality, and reduce manufacturing cost of advanced gas turbine engine divergent flaps.
Funding: ($000)	**Total Estimated Cost:** $750

Prior Investment	FY93	FY94	FY95	Cost to Complete
$750	$0	$0	$0	$0

Milestones:	9/91 Start. 5/95 Completion.
Reference:	1992 Project Book, p. 128

Title:	Titanium Matrix Composite Initiative: Mode Strut
Performing Agency:	Air Force
Status:	Funded
Description:	Define a cost-effective manufacturing process for the nozzle mode strut of the F100-PW229 engine. Improve pre-form manufacture by tape casting.
Funding: ($000)	**Total Estimated Cost:** $565

Prior Investment	FY93	FY94	FY95	Cost to Complete
$565	$0	$0	$0	$0

Milestones:	8/91 Start. 1/94 Completion.
Reference:	1992 Project Book, p. 128

Title:	Titanium Matrix Composite Initiative: Ring Inserts
Performing Agency:	Air Force
Status:	Funded
Description:	Optimize the producibility, improve the quality, and reduce the manufacturing cost of ring inserts for compressor rotors of advanced gas turbine engines. Establish a continuous tape casting pre-form process, automate pre-form layup, and demonstrate multi-part tool fixturing.
Funding: ($000)	**Total Estimated Cost:** $1,435

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,435	$0	$0	$0	$0

Milestones:	9/91 Start. 2/95 Completion. Fabricate different size ring inserts out of 10 different matrix alloys.
Reference:	1992 Project Book, p. 128

Title: Welded Titanium Aircraft Structures

Performing Agency: Air Force

Status: Funded

Description: Produce large, structurally efficient, welded Ti assemblies for advanced fighter aircraft primary structures.

Funding: ($000)

Total Estimated Cost: $6,150

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$150	$2,100	$0	$3,900

Milestones:
Est. 8/93 Start. No Completion date yet specified.
Phase I: Identify candidate fighter aircraft primary structures.
Phase II: Demonstrate weld processes, tooling, and quality procedures.
Phase III: Fabricate full-scale test articles.

Reference: 1992 Project Book, p. 145

Title: Application of Refractory Coatings by Sputtering

Performing Agency: Army

Status: Funded

Description: Task #8553. Develop a sputtering system to deposit refractory metals (vice currently used chromium) to the interior of large-caliber cannon bores, at temperatures down to 70C.

Funding: ($000)

Total Estimated Cost: $1,030

Prior Investment	FY93	FY94	FY95	Cost to Complete
$710	$320	$0	$0	$0

Milestones:

Reference: FY93/94 Info. Summary, p. 57

Precision Fabrication Projects

Title: Automatic Image Recognition and Manipulation

Performing Agency: Army

Status: Funded

Description: Task #T701. Design a general-purpose system for the sorting and assembly of fuze components. The system should be self-teaching (artificially intelligent) and capable of handling parts presented in random orientations.

Funding: ($000)

Total Estimated Cost: $1,200

Prior Investment	FY93	FY94	FY95	Cost to Complete
$860	$340	$0	$0	$0

Milestones:

Reference: FY93/94 Info. Summary, p. 62

Title: Dimensional Gauging of Engine Components

Performing Agency: Army

Status: Funded

Description: Task #T705. Develop a digital gauging system to measure, during setup and processing, production parts in the RRAD 6V53 diesel engine rebuild facility.

Funding: ($000)

Total Estimated Cost: $532

Prior Investment	FY93	FY94	FY95	Cost to Complete
$437	$95	$0	$0	$0

Milestones:

Reference: FY93/94 Info. Summary, p. 64

Title: Ductile Iron Casting

Performing Agency: Army

Status: Funded

Description: Characterize material, develop test specifications, develop process models, establish producer certification standards, and implement a manufacturing cell at the Rock Island Arsenal. Demonstrate on 155mm M864 round, 155mm XM982 round, and tank track systems. Congressionally directed.

Funding: ($000)

Total Estimated Cost: $23,600

Prior Investment	FY93	FY94	FY95	Cost to Complete
$11,000	$3,100	$2,000	$500	$7,000

Milestones:
Complete characterization, specifications, standards, and models in 1993.
Build Rotating Band Welding machine in 1993; prove-out in 1994.
Complete ammunition demonstrations in 1995.
Funds beyond FY95 for testing of tank treads and suspensions in 1997.

Reference: F. del Carmen

Title: Environmentally Acceptable Processes

Performing Agency: Army

Status: Funded

Description: Task #9001. Develop techniques to reduce pollution, ensure environmental compliance, and increase worker safety while maintaining industrial capability. Initial focus on Volatile Organic Compounds, CFCs, hydrocarbons, and halons. Manufacturing operations commonly affected include painting, plating, and

Funding: ($000)

Total Estimated Cost: $4,423

Prior Investment	FY93	FY94	FY95	Cost to Complete
$2,941	$1,132	$0	$0	$350

Milestones:

Reference: FY93/94 Info. Summary, p. 58

Title: Flexible Ammunition

Performing Agency: Army

Status: Funded

Description: Congressionally directed. At Scranton ammunition plant.

Funding: ($000)

Total Estimated Cost: $7,500

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$7,500	$0	$0	$0

Milestones:

Reference: Bill Donnelly

Title: Improved Broaching of UDIMET 720

Performing Agency: Army

Status: Funded

Description: Task #7605. Develop an improved technology for the broaching blade mounting slots in UDIMET 720 turbine engine disks. These disks are used in T800 and T406 engines. Examine broach material, design, and process parameters. Improvements will also apply to disks made from Waspaloy and Astroloy (all Ni-based superalloys).

Funding: ($000)

Total Estimated Cost: $450

Prior Investment	FY93	FY94	FY95	Cost to Complete
$250	$200	$0	$0	$0

Milestones:

Reference: FY93/94 Info. Summary, p. 56

Precision Fabrication Projects

Title:	Materials Testing Technology
Performing Agency:	Army
Status:	Funded
Description:	Task #6350. Provide new methods for inspection or process control of materiel in or scheduled for production, in service, in storage, or undergoing rebuild.
Funding: ($000)	
Total Estimated Cost:	$7,613

Prior Investment	FY93	FY94	FY95	Cost to Complete
$5,024	$659	$0	$0	$1,930

Milestones:

Reference: FY93/94 Info. Summary, p. 55

Title:	Medium Duty Mat
Performing Agency:	Army
Status:	Funded
Description:	Task #3868. Develop a manufacturing process for fabricating landing mat using all-bonded techniques, eliminating the need for clean-room and welding.
Funding: ($000)	
Total Estimated Cost:	$491

Prior Investment	FY93	FY94	FY95	Cost to Complete
$256	$235	$0	$0	$0

Milestones:

Reference: FY93/94 Info. Summary, p. 52

Title:	Optical Process Planning
Performing Agency:	Army
Status:	Funded
Description:	Task #9060. Develop a generative process planner/cost estimator that allows optical systems designers to make cost, design, and manufacturing trade-offs using a CAD workstation.
Funding: ($000)	Total Estimated Cost: $2,369
Milestones:	
Reference:	FY93/94 Info. Summary, p. 60

Prior Investment	FY93	FY94	FY95	Cost to Complete
$619	$0	$0	$0	$1,750

Title:	OPTICAM for Spherical Grinding and Finishing
Performing Agency:	Army
Status:	Funded
Description:	Task #8934. Develop 5-axis CNC machinery for the fabrication of tight-tolerance, single-lens optics. Features include closed-loop lens measurement and tool wear compensation and parametric programming of generic spherical surfaces.
Funding: ($000)	Total Estimated Cost: $3,848
Milestones:	
Reference:	FY93/94 Info. Summary, p. 58

Prior Investment	FY93	FY94	FY95	Cost to Complete
$2,580	$472	$0	$0	$796

Title: Parameters of Lens Grinding

Performing Agency: Army

Status: Funded

Description: Task #9059. Perform quantitative analyses of the key parameters in lens grinding and polishing. Develop a generic, statistically-based optimum process for the primary glasses most used in military optics.

Funding: ($000)

Total Estimated Cost: $3,418

Prior Investment	FY93	FY94	FY95	Cost to Complete
$868	$550	$0	$0	$2,000

Milestones:

Reference: FY93/94 Info. Summary, p. 60

Title: Prism Blocking

Performing Agency: Army

Status: Funded

Description: Task #9033. Develop tooling for use with the OPTICAM PM machining center. Tooling should be compatible with automatic tool changers, should handle a wide variety of prisms, and feature quick setup.

Funding: ($000)

Total Estimated Cost: $2,373

Prior Investment	FY93	FY94	FY95	Cost to Complete
$573	$400	$0	$0	$1,400

Milestones:

Reference: FY93/94 Info. Summary, p. 59

Title: Production and Casting of Barium-Strontium-Titanate

Performing Agency: Army

Status: Funded

Description: Task #3223. Develop mass production techniques that improve yield and throughput of ferrite phase shifters. Meet requirements for dynamic temperature range, hysteresis, and magnetic flux effects.

Funding: ($000)

Total Estimated Cost: $241

Prior Investment	FY93	FY94	FY95	Cost to Complete
$150	$91	$0	$0	$0

Milestones:

Reference: FY93/94 Info. Summary, p. 52

Title: Production Engineering Tools

Performing Agency: Army

Status: Funded

Description: Task #TA14. Develop analytical tools that permit producibility analyses during the concept development stage of weapon system design. Include product simplification rules, materials selection data, design standards for integration, quality and tooling data, and facilities considerations.

Funding: ($000)

Total Estimated Cost: $4,579

Prior Investment	FY93	FY94	FY95	Cost to Complete
$2,579	$375	$0	$0	$1,625

Milestones:

Reference: FY93/94 Info. Summary, p. 66

Title: Ultrasonic Tube Wall Thickness

Performing Agency: Army | **Status:** Funded

Description: Task #T710. Develop automatic equipment and software to measure finished gun tube thickness. Evolve from current manual process.

Funding: ($000) Total Estimated Cost: $130

Prior Investment	FY93	FY94	FY95	Cost to Complete
$73	$57	$0	$0	$0

Milestones:

Reference: FY93/94 Info. Summary, p. 64

Title: Fastener Identification and Validation System Development

Performing Agency: DLA | **Status:** Funded

Description: Develop tools for performing receiving-inspection of selected geometric and metallurgical fastener attributes. Validate that received material quality corresponds to order and identify material that arrives with improper documentation.

Funding: ($000) Total Estimated Cost: $250

Prior Investment	FY93	FY94	FY95	Cost to Complete
	$0	$0	$0	$0

Milestones:
7/91 Start. 9/94 Completion.
Beta test at Defense Depot Sesquehanna, Pennsylvania.
Identify an unknown item in less than one minute.

Reference: Dan Gearing

Title: Vision and Imaging Processes for Gear Inspection and Production

Performing Agency: DLA

Status: Funded

Description: Studies to replace human visual inspection of aircraft gears with video cameras and image-processing computers. Establish basis for application to any product requiring detection of surface flaws.

Funding: ($000)

Total Estimated Cost: $300

Prior Investment	FY93	FY94	FY95	Cost to Complete
$300	$0	$0	$0	$0

Milestones: 4/91 Start. 5/94 Completion.
Demonstrate quality and resolution of video images to detect and discriminate among surface flaws.
Develop a prototype operator-assisted computer vision system to perfor[illegible] exterior flaw detection, interior flaw detection, and spiral bevel gear contact pc[illegible] analysis.

Reference: Dan Gearing

Title: Acceptability of Surface Preparation Cleaners

Performing Agency: Navy

Status: Funded

Description: Determine the environmental acceptability, health, and safety requirements for shipyard use. Determine benefit to corrosion control performance provided by various cleaners used for surface preparation of ship hull steel substrates.

Funding: ($000)

Total Estimated Cost: $103

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$103	$0	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title: Advanced Consumables for Welding 80-100 ksi Strength Steels

Performing Agency: Navy

Status: Funded

Description: Develop filler wire metal for welding HSLA-80 and HSLA-100 (High-Strength, Low Alloy) steels (also can be applied to HY-80 and HY-100 steels).

Funding: ($000)

Total Estimated Cost: $887

Prior Investment	FY93	FY94	FY95	Cost to Complete
$789	$98	$0	$0	$0

Milestones: Start 10/90. Completion 9/93.
100S-derivative wire with yield strength = 82 ksi in matched applications and 88 ksi in undermatched applications.
120S-derivative wire with yield strength = 102 ksi in non-undermatched applications.
Alloy optimization to be considered in a follow-on project.

Reference: 1992 Project Book, p. 112

Title: Advanced Machine Tool Controllers

Performing Agency: Navy

Status: Funded

Description:

Funding: ($000)

Total Estimated Cost: $2,350

Prior Investment	FY93	FY94	FY95	Cost to Complete
$500	$550	$650	$0	$650

Milestones: Phase I: Demonstrate a simple open architecture controller on a Monarch machining center.
Phase II: Build a prototype controller based on NGC open architecture. Include capability to emulate Allen-Bradley, GE 2000, and Fanuc 10 controllers.

Reference: Navy ManTech Program Summary

Precision Fabrication Projects

Title:	Advanced Machine Tool Structures
Performing Agency:	Navy
Status:	Funded
Description:	Design and build a prototype multi-axis machining center with greater accuracy and flexibility than currently available. Note: cooperative effort with Ingersol Milling; NIST will develop a metrology system to coordinate and monitor machine activities.
Funding: ($000)	**Total Estimated Cost:** $1,500

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$425	$475	$0	$600

Milestones:	
Reference:	Navy ManTech Program Summary

Title:	Advanced Propulsor Manufacturing Technology
Performing Agency:	Navy
Status:	Funded
Description:	Develop and integrate blade manufacturing cell, NC abrasive finishing, and laser inspection technologies. Apply to SSN-21 propulsor and surface combatant controllable-pitch propellers.
Funding: ($000)	**Total Estimated Cost:** $0

Prior Investment	FY93	FY94	FY95	Cost to Complete
	$0	$0	$0	$0

Milestones:	Start 3/91. On-going. Funding data not available.
Reference:	1992 Project Book, p. 120

Precision Fabrication Projects

Title:	Advanced Refurbishment of Engine Parts
Performing Agency:	Navy
Status:	Funded
Description:	Pursue braze and weld improvements to J52 turbine engine airfoil crack repair at Naval Aviation Depot, Cherry Point.
Funding: ($000)	**Total Estimated Cost:** $2,985

Prior Investment	FY93	FY94	FY95	Cost to Complete
$637	$1,698	$650	$0	$0

Milestones:

Start 6/91. Completion 10/94.
Phase I: Needs analysis.
Phase II: Adapt turbofix braze for various vane alloys and automate shroud welding.
Phase III: Qualify vane repair, blade repair, and coating processes.

Reference: 1992 Project Book, p. 178

Title:	Application of Neural Nets in Motion Control
Performing Agency:	Navy
Status:	Funded
Description:	Assess the feasibility of using neural networks in real-time, adaptive, non-linear control of motion in machine tools.
Funding: ($000)	**Total Estimated Cost:** $110

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$110	$0	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title:	Automated Deburring and Chamfering System
Performing Agency:	Navy
Status:	Funded
Description:	Develop an automated deburring system that can be utilized on close tolerance gas turbine engine components. The system will include: sensor-based control, a process model, and enhanced tool design.
Funding: ($000)	**Total Estimated Cost:** $1,479

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,479	$0	$0	$0	$0

Milestones:	Start 9/89. Completion 9/93.
Reference:	1992 Project Book, p. 24

Title:	Casting of XD Intermetallic Matrix Composites
Performing Agency:	Navy
Status:	Funded
Description:	Develop technologies for predicting significant events associated with the centrifugal casting of complexly-shaped components made of TiAl-based alloys and composites.
Funding: ($000)	**Total Estimated Cost:** $222

Prior Investment	FY93	FY94	FY95	Cost to Complete
$167	$55	$0	$0	$0

Milestones:	Design the SLAT missile fin to have minimum weight. Determine how to quickly make a quality, low-cost casting of a gun blast diffuser.
Reference:	Navy ManTech Program Summary

Title:	Casting Technology Development
Performing Agency:	Navy
Status:	Funded
Description:	Improve the prediction and control of casting through the application of RAPID/CAST, a 3-D casting design software program. Software modules include: geometry creation, mesh generation, mold materials, and process characterization.
Funding: ($000)	**Total Estimated Cost:** $12,214

Prior Investment	FY93	FY94	FY95	Cost to Complete
$3,551	$1,863	$1,700	$0	$5,000

Milestones:	Start 4/90. Completion 5/94.
Reference:	1992 Project Book, p. 152

Title:	Coordinate Measuring Machines (CMMs)
Performing Agency:	Navy
Status:	Funded
Description:	Determine current DoD and industry needs for CMMs.
Funding: ($000)	**Total Estimated Cost:** $1,210

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$110	$500	$0	$600

Milestones:	
Reference:	Navy ManTech Program Summary

Title: Critical Screw Thread Measurement

Performing Agency: Navy **Status:** Funded

Description: Perform research on gaging methods and develop approaches for compliance with MIL-STD-8879C and PL101-592. Develop a bibliography of screwthread literature, determine the effectiveness of single-element gaging, and recommend changes to ANSI standards bringing U.S. practice closer to international practice.

Funding: ($000) **Total Estimated Cost:** $210

Prior Investment	FY93	FY94	FY95	Cost to Complete
$100	$110	$0	$0	$0

Milestones: Start 10/91. On-going.
Implement improvements at Pensacola Naval Aviation Depot.

Reference: 1992 Project Book, p. 44

Title: Diamond Turning

Performing Agency: Navy **Status:** Funded

Description: Develop a better understanding of the causes of tool wear in single-point diamond turning. The principle application is optics (mirrors). Reduce wear-induced scatter in optical workpieces. Materials turned include steel, Be, Mo, and Ti.

Funding: ($000) **Total Estimated Cost:** $180

Prior Investment	FY93	FY94	FY95	Cost to Complete
$180	$0	$0	$0	$0

Milestones: Start 10/90. Completion 9/96.
Develop theory of chemically-induced tool wear.
Develop lapping techniques that improve finish without harming figure.

Reference: 1992 Project Book, p. 158

Precision Fabrication Projects

Title: Electroslag Surfacing Technology

Performing Agency: Navy

Status: Funded

Description: Demonstrate the application of electroslag surfacing (ESS) to the building and overhaul of Naval vessel main propulsion shafts. ESS is a promising alternative to submerged arc surfacing, offering double the deposition rate.

Funding: ($000)

Total Estimated Cost: $4,622

Prior Investment	FY93	FY94	FY95	Cost to Complete
$3,087	$1,535	$0	$0	$0

Milestones:
Start 10/90. Completion 9/93.
Process development and optimization.
Validation testing.
Development of non-destructive test technique.

Reference: 1992 Project Book, p. 164

Title: Fabrication Process for High Temperature PM Aluminum Impellers

Performing Agency: Navy

Status: Funded

Description: Demonstrate application of powder-metal Al alloys (X8019 and 8009) to turbine compressor components with service temperatures up to 650F. Replace the current Ti forging in the GTC36-200 APU impeller aboard the F/A-18.

Funding: ($000)

Total Estimated Cost: $1,809

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,809	$0	$0	$0	$0

Milestones:
Start 11/90. Completion 5/94.
Phase I: Screen potential alloys and optimize manufacturing processes.
Phase II: Using selected material, build impeller, test in the APU, and compile a material design database.

Reference: 1992 Project Book, p. 144

Precision Fabrication Projects

Title:	Increasing Machine Precision
Performing Agency:	Navy
Status:	Funded
Description:	Implement predictive and prescriptive compensation strategies, with emphasis on software enhancements rather than hardware modifications.
Funding: ($000)	**Total Estimated Cost:** $2,510

Prior Investment	FY93	FY94	FY95	Cost to Complete
$350	$660	$750	$0	$750

Milestones:	Improve the performance of existing machine tools an order of magnitude.
Reference:	Navy ManTech Program Summary

Title:	Intelligent Processing of Materials
Performing Agency:	Navy
Status:	Funded
Description:	Develop intelligent processing methods for the manufacture of discrete near-net-shape components.
Funding: ($000)	**Total Estimated Cost:** $118

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$118	$0	$0	$0

Milestones:	
Reference:	Navy ManTech Program Summary

Precision Fabrication Projects

Title: Intelligent Weld Process (WELDEXCELL)

Performing Agency: Navy

Status: Funded

Description: Demonstrate feasibility of weld planning software that helps the weld engineer select electrodes and process parameters based on material and part requirements. Demonstrate the feasibility of a weld cell controller that initializes a weld robot controller and performs seam tracking and process control (removing the operator

Funding: ($000)

Total Estimated Cost: $3,690

Prior Investment	FY93	FY94	FY95	Cost to Complete
$3,690	$0	$0	$0	$0

Milestones: Start 12/87. Completion 9/94.
Install system at Puget Sound Naval Shipyard.

Reference: 1992 Project Book, p. 8

Title: Laser Corrosion Cladding

Performing Agency: Navy

Status: Funded

Description: Development of a laser-cladding process for applying corrosion-resistant coatings to HY steel structures. Apply to submarine hull components such as electrical cable inserts and piping inserts.

Funding: ($000)

Total Estimated Cost: $200

Prior Investment	FY93	FY94	FY95	Cost to Complete
$200	$0	$0	$0	$0

Milestones: Start 11/90. On-going.
Phase I: Develop process parameters for clad and base materials. Demonstrate relaxation of preheat and interpass temperature control for HY-80 steel base.
Phase II: Demonstrate cladding process on specific hull components.

Reference: 1992 Project Book, p. 168

Precision Fabrication Projects

Title: Laser Materials Processing

Performing Agency: Navy **Status:** Funded

Description: Develop, qualify, and transfer laser material processing technologies. Includes laser cladding of hardfacing and corrosion resistant m[illegible]als, laser welding of NAB, LASCOR design, and development of portable las[illegible] [illegible]r docks[illegible]de applications.

Funding: ($000) Total Estimated Cost: $9,700

Prior Investment	FY93	FY94	FY95	Cost to Complete
$5,800	$1,700	$500	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title: Linear Friction Welding

Performing Agency: Navy **Status:** Funded

Description: Assess the viability of linear friction welding in NAVAIR applications.

Funding: ($000) Total Estimated Cost: $194

Prior Investment	FY93	FY94	FY95	Cost to Complete
$170	$24	$0	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title: Materials Standards For Powdered Metal Alloys

Performing Agency: Navy **Status:** Funded

Description: Measure and compile mechanical and physical property data for P/M alloys. Standard properties of strength and ductility will be augmented with wear, corrosion, fatigue, and machinability.

Funding: ($000) **Total Estimated Cost:** $2,975

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,487	$1,188	$300	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title: Meta-Lax Vibratory Stress Relief Process

Performing Agency: Navy **Status:** Funded

Description: Evaluate vibratory relief of residual stresses in gas-metal arc weldments. Compare to traditional thermal relief. Evaluate for HY-80 steel, 5456 aluminum, and A36 steel.

Funding: ($000) **Total Estimated Cost:** $161

Prior Investment	FY93	FY94	FY95	Cost to Complete
$115	$46	$0	$0	$0

Milestones:

Reference: 1992 Project Book, p. 124

Title:	Metal Matrix Composites Program
Performing Agency:	Navy
Status:	Funded
Description:	Establish efficient manufacturing techniques for producing cast, discontinuously-reinforced aluminum structural hardware.
Funding: ($000)	Total Estimated Cost: $1,500

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$250	$750	$0	$500

Milestones:	
Reference:	Navy ManTech Program Summary

Title:	Mobility for Robotic Welding
Performing Agency:	Navy
Status:	Funded
Description:	Assess the potential for using robots to increase the mobility of current welding technologies.
Funding: ($000)	Total Estimated Cost: $85

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$85	$0	$0	$0

Milestones:	Report summarizing project potential.
Reference:	Navy ManTech Program Summary

Title:	Modern Casting Technology for Ammunition
Performing Agency:	Navy
Status:	Funded
Description:	Demonstrate feasibility of using cast ductile iron in the fabrication of major caliber ammunition (including 5 inch and 76 mm).
Funding: ($000)	**Total Estimated Cost:** $10,549

Prior Investment	FY93	FY94	FY95	Cost to Complete
$10,549	$0	$0	$0	$0

Milestones:
Start 8/90. Completion 8/95.
Phase I: Finite stress and thermal models.
Phase II: Casting trials leading to 6 consecutive castings meeting requirements.
Phase III: Refinement of pattern/core design and casting process, leading to 100 castings.
Phase IV: Testing and compatability demonstration.

Reference: 1992 Project Book, p. 130

Title:	National Joining Center
Performing Agency:	Navy
Status:	Funded
Description:	
Funding: ($000)	**Total Estimated Cost:** $20,000

Prior Investment	FY93	FY94	FY95	Cost to Complete
$10,000	$0	$10,000	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Precision Fabrication Projects

Title: NCEMT Rapid Response

Performing Agency: Navy **Status:** Funded

Description: Respond to immediate technical problems. Recent examples include: hull cutting, EA-6B arresting hook, and T2-C hat section.

Funding: ($000) **Total Estimated Cost:** $8,671

Prior Investment	FY93	FY94	FY95	Cost to Complete
$4,181	$890	$900	$0	$2,700

Milestones:

Reference: Navy ManTech Program Summary

Title: New Surface Preparation and Coating Repair Techniques in Ballast Tanks

Performing Agency: Navy **Status:** Funded

Description: Test and evaluate immersion-grade coating systems in the mock-up ballastic tanks at Jacksonville, FL. Scope includes surface-tolerant and VOC-compliant coatings.

Funding: ($000) **Total Estimated Cost:** $59

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$59	$0	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title: Optimization of Small-size Fillet Welds

Performing Agency: Navy **Status:** Funded

Description: Develop techniques and equipment to manufacture 1/8 inch fillet welds semi-automatically.

Funding: ($000) **Total Estimated Cost:** $75

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$75	$0	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title: Optimized Weldment Properties in HY-100 Steel Submarine Structures

Performing Agency: Navy **Status:** Funded

Description: Develop optimized weld properties (yield strength) for HY-100 steel. Explore undermatching weld filler to structural materials.

Funding: ($000) **Total Estimated Cost:** $2,491

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,511	$980	$0	$0	$0

Milestones:
Start 4/91. Completion 7/93.
Formulate HY-100 steel weld fabrication documents.
Validation/Certification Plan for SSN-21 pressure hull weld system.
Methodology to analyze mechanical response of weld joints.

Reference: 1992 Project Book, p. 122

Title: Plasma Spray Sensor Development

Performing Agency: Navy

Status: Funded

Description: Assess the potential for integrating sensor-based inspection techniques into the plasma spray cell being developed at NCEMT.

Funding: ($000)

Total Estimated Cost: $50

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$50	$0	$0	$0

Milestones: Report summarizing the potential for a joint AMRF/NCEMT project.

Reference: Navy ManTech Program Summary

Title: Plasma Spray/CNC Integration

Performing Agency: Navy

Status: Funded

Description: Integrate plasma spray and CNC technologies into an automated system for shipyard part repair. Major equipment components to be integrated are: vertical bed turning center, grit blaster, digital control plasma thermal spray unit, dust collection unit, and cell controller.

Funding: ($000)

Total Estimated Cost: $3,933

Prior Investment	FY93	FY94	FY95	Cost to Complete
$3,015	$778	$140	$0	$0

Milestones:
Start 1/90. Completion 9/93.
Phase I: System definition.
Phase II: Prototype system development.
Phase III: Installation at Puget Sound Naval Shipyard.

Reference: 1992 Project Book, p. 10

Title: Powder Injection Molding

Performing Agency: Navy

Status: Funded

Description: Develop PIM alternatives to small, complex-shaped parts currently machined from bar stock and castings. Identify potential NAVAIR applications, qualify the process for NAVAIR application, and demonstrate on a production part.

Funding: ($000)

Total Estimated Cost: $5,099

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,190	$1,209	$2,200	$0	$500

Milestones: Start 1/91. Completion 5/95.
Phase I: Optimize PIM modeling software
Phase II: Select potential applications
Phase III: Apply modeling software to selected parts and fabricate

Reference: 1992 Project Book, p. 148

Title: Powder Metallurgy Initiative

Performing Agency: Navy

Status: Funded

Description: Address key technologies critical to the application of powdered-metal parts to DoD systems. Evaluate quality issues, new processes, new materials, and design concepts.

Funding: ($000)

Total Estimated Cost: $7,296

Prior Investment	FY93	FY94	FY95	Cost to Complete
$2,197	$1,099	$1,000	$0	$3,000

Milestones: Start 3/90. Completion 9/95.

Reference: 1992 Project Book, p. 154

Title: Precision Electro-mechanical Actuators

Performing Agency: Navy

Status: Funded

Description: Study the use of precision electro-mechanical actuators in servo systems for single point turning of complex geometries. Concentrate on high-stiffness, low-weight materials. Develop a prototype linear actuator-based fast tool servo with voice coil and ceramic ram.

Funding: ($000)

Total Estimated Cost: $110

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$110	$0	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title: Precision Machining of Advanced Materials

Performing Agency: Navy

Status: Funded

Description: Develop a facility that contains a wide range of computer-controlled machines for fabricating high-precision components from advanced materials. Conduct research in ceramic grinding, diamond turning, and hard turning.

Funding: ($000)

Total Estimated Cost: $2,660

Prior Investment	FY93	FY94	FY95	Cost to Complete
$500	$660	$750	$0	$750

Milestones:

Reference: Navy ManTech Program Summary

Title: Quality in Automation

Performing Agency: Navy **Status:** Funded

Description: Develop a closed-loop quality control architecture for discrete part manufacturing. Focus on 1) improve machine tool structural components, 2) modify feedback systems to compensate for systematic machine tool errors, 3) provide in-process and process-intermittent measurements of part errors, and 4) provide post-process

Funding: ($000) **Total Estimated Cost:** $450

Prior Investment	FY93	FY94	FY95	Cost to Complete
$450	$0	$0	$0	$0

Milestones: Start 10/90. Completion 9/93.

Reference: 1992 Project Book, p. 36

Title: Robotic Grinding of Weld Beads

Performing Agency: Navy **Status:** Funded

Description: Assess the potential for using robotics to increase the efficiency of automated grinding of weld beads.

Funding: ($000) **Total Estimated Cost:** $85

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$85	$0	$0	$0

Milestones: Report summarizing project potential.

Reference: Navy ManTech Program Summary

Title:	Semi-solid Metalworking
Performing Agency:	Navy
Status:	Funded
Description:	Explore the status of semi-solid metalworking technology, which incorporates elements of casting and forging to produce very low porosity parts. Identify potential Navy applications and barriers to its use.
Funding: ($000)	**Total Estimated Cost:** $10,000

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$4,000	$3,000	$0	$3,000

Milestones:

Reference: Navy ManTech Program Summary

Title:	Sensory Feedback in Adaptive Machining
Performing Agency:	Navy
Status:	Funded
Description:	
Funding: ($000)	**Total Estimated Cost:** $1,850

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$550	$650	$0	$650

Milestones:

Reference: Navy ManTech Program Summary

Title:	Spray Metal Forming
Performing Agency:	Navy
Status:	Funded
Description:	Demonstrate a near-net-shape spray metal forming process for components made of Inconel 625 (Ni-based superalloy for torpedo tubes, shaft seals, sleeves, and bearings; gas turbine engine applications). Congressionally directed.
Funding: ($000)	**Total Estimated Cost:** $12,000

Prior Investment	FY93	FY94	FY95	Cost to Complete
$12,000	$0	$0	$0	$0

Milestones:
Start 11/90. Completion 9/94.
Define scaling parameters to expand pilot line to large-scale facility.
Build large-scale facility.
Confirm process controls by certification of full-scale components.

Reference: 1992 Project Book, p. 119

Title:	Thermomechanical Processing of Gears
Performing Agency:	Navy
Status:	Funded
Description:	Develop a double-die ausrolling machine that integrates induction heat treatment and gear rolling. Machine capability to include up to 8 inch diameter gears with tooth pitches between 6 and 32. Demonstrate on a 5.2 inch, 8.1 pitch diameter spur gear.
Funding: ($000)	**Total Estimated Cost:** $5,137

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,137	$1,000	$0	$0	$2,000

Milestones:
Start 10/88. Completion 9/93.
Specification and construction of induction heating machine and controller.
Specification and construction of ausroller and controller.
Integration of ausroller and heating modules.

Reference: 1992 Project Book, p. 146

Title: Thick Section Welding with Fiber Optic Delivered Nd:YAG Laser

Performing Agency: Navy **Status:** Funded

Description: Develop a concept design and specification for an automated shipboard system. Develop weld process parameters.

Funding: ($000) **Total Estimated Cost:** $125

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$125	$0	$0	$0

Milestones:

Reference: Navy ManTech Program Summary

Title: Titanium-Aluminide XD Composite

Performing Agency: Navy **Status:** Funded

Description: Processing of TiAl intermetallic alloys reinforced with TiB2 particles. Prepare ingots and near-net-shape castings; establish parameters for rolling, forging, extruding, pressing, and superplastic forming into airframe and engine components; fabricate demonstration components; generate data for MIL-HDBK-5.

Funding: ($000) **Total Estimated Cost:** $1,784

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,784	$0	$0	$0	$0

Milestones:
Start 10/90. Completion 12/93.
Phase I: Assess existing manufacturing capabilities of the XD process
Phase II: Scale-up casting process for XD TiAl.
Phase III: Demonstrate production of SLAT missile fin and F/A-18 gun blast diffuser.
Phase IV: Production scale-up, component tests, and flight qualification.

Reference: 1992 Project Book, p. 134

Title: Tungsten Alloy Penetrators

Performing Agency: Navy

Status: Funded

Description: Demonstrate advanced materials, processes, and designs for W alloy penetrators used in the Block II Phalanx system. Explore the effects of Fe/Ni and Co/Ni liquid-phase matrix alloys on penetrator processing and performance. Investigate roll forming and powder metal processes.

Funding: ($000)

Total Estimated Cost: $2,298

Prior Investment	FY93	FY94	FY95	Cost to Complete
$1,309	$989	$0	$0	$0

Milestones: Start 5/91. Completion 9/93.

Reference: 1992 Project Book, p. 132

Title: Ultrasonic Sensors

Performing Agency: Navy

Status: Funded

Description: Monitor, in-process, the surface finish of gas turbine engine shafts and discs via a signal coupled by the coolant stream of a CNC lathe.

Funding: ($000)

Total Estimated Cost: $155

Prior Investment	FY93	FY94	FY95	Cost to Complete
$155	$0	$0	$0	$0

Milestones: Start 10/91. Completion 9/93.
Resolve average surface roughness to submicron accuracy over a nominal rougness range from 0 to several microns.

Reference: 1992 Project Book, p. 26

Title:	Videotapes on Advanced Ship Production
Performing Agency:	Navy
Status:	Funded
Description:	Develop a video short course on concepts of advanced ship production for presentation to shipyard skilled trades and apprentice school programs.
Funding: ($000)	**Total Estimated Cost:** $62
Milestones:	
Reference:	Navy ManTech Program Summary

Prior Investment	FY93	FY94	FY95	Cost to Complete
$0	$62	$0	$0	$0

Title:	Workability Test System "Atlas of Formability"
Performing Agency:	Navy
Status:	Funded
Description:	Develop a reference book incorporating forming materials' mechanical properties and microstructural data for deformation process optimization. Mechanical properties include: stress-strain at elevated temperature, workability, and forming limits. Materials include Al 6061, Al 7050, chromium steel, Inconel 600, and Inconel
Funding: ($000)	**Total Estimated Cost:** $6,893
Milestones:	Start 1/90. Completion 9/94.
Reference:	1992 Project Book, p. 150

Prior Investment	FY93	FY94	FY95	Cost to Complete
$2,391	$902	$900	$0	$2,700