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**Technical Assessment of Engineering's
Manufacturing Technology Thrust Area at
Lawrence Livermore National Laboratory**

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Technical Assessment of Engineering's Manufacturing Technology Thrust Area at Lawrence Livermore National Laboratory

K. L. Blaedel

Abstract

This document investigates the connection between the Manufacturing Technology Thrust Area and its market and concludes that the connection should include the programs internal to LLNL and customers outside of LLNL. The thrust area's existing mission is reviewed and while it remains relevant to the future, it is too broad for the assigned resources. The scope of the thrust area's mission is therefore narrowed to more specifically address precision in manufacturing. The course to pursue the new focus is plotted, and the projects for FY95 are briefly discussed.

Current Activity in the Manufacturing Technology Thrust Area

The *mission* of the thrust area has been to have an adequate base of manufacturing technology, not necessarily resident at LLNL, to conduct the future business of LLNL. Our specific goals have been to

- develop an understanding of fundamental fabrication processes;
- construct general purpose process models that will have wide applicability;
- document our findings and models in journals;
- transfer technology to LLNL programs, industry, and colleagues; and
- develop continuing relationships with the industrial and academic communities to advance our collective understanding of fabrication processes.

The *criterion for success* of the thrust area has been difficult to define. For each project, merely meeting the milestones of the projects is a measure of success. A better indication of how well a project was constructed occurs when a technology that began as a funded effort in the thrust area is then picked up for funding by another source such as a program. The programmatic continuation of the technology is often embodied as a specific application rather than as the more generic effort of the thrust area. The transferal to a new funding source demonstrates that the thrust area took a risk to develop a technology of future value to a program or programs. The reason this is only an indicator of success of a project is that although the thrust area has created goodwill by addressing a

future need of a program, it is unclear how goodwill leads to the future existence and funding of the thrust area, more direct measures of success.

Perhaps a better indication of success of the thrust area as a whole is demonstrated when a program or other customer approaches the thrust area to help develop future technology rather than current method where the thrust area approaches a program to solicit what technologies have future importance and need further developing.

The relationship of the thrust area to the programs depends heavily on how well the thrust area and its technology is marketed to its customers, an aspect which the thrust area has tended to undervalue in the past. This activity is necessary to transition to other funding, but has not until recently been a directly funded project activity.

The most harsh measure of success is whether a thrust area funded technology does indeed become critical to a program three to five years later. This gauge gives evaluation only after the fact and does not give continuous corrective guidance to the thrust area as it evolves. The gage of whether a predicted technological becomes critical to a program is not simply hit-or-miss, that is, if indeed a supported technology misses the mark and does not become a critical need to a program, it is not as though resources have been totally wasted; the technology developed by a thrust area should be somewhat generic and apply to more than a single program or application. This has been an important criterion for selection of projects within the thrust area.

The *purview of the thrust area* has traditionally been broad. Table 1 lists the titles of projects pursued (including engineering development) for the last ten years. The majority can be partitioned into the following main areas:

Metrology. The application of metrology has always been strongly driven by LLNL internal programs. Developing instrumentation and techniques for measurement has enjoyed enduring support by the thrust area.

Material Deposition Processes. The thrust area has aided the development of techniques and equipment to produce thin-film coatings at high rate and high quality by physical and chemical vapor deposition.

Material Removal Processes. Diamond turning, grinding of brittle materials, and polishing of glass have all benefited from long-term thrust area interest.

Process Modeling. Understanding a material removal process is important to applying that process in actual fabrication. This arena has often been difficult to support directly from a program and thus has received continued support from the thrust area. Much of the early support for molecular dynamic simulation has come from the thrust area.

Table 1. Development projects funded in manufacturing technology over the past decade. The titles that appear in boldface type represent projects that focused on some aspect of precision in manufacturing.

FY	Project Titles
1985	Residual Stress Analysis of Weaving Weld Patterns on 304 Stainless Steel Topometric Interferometry Chip Science: Basic Study of the Single-Point Cutting Process Precision Contouring of Brittle Materials Development of Precision Material-Removal Processes for Low-Density Foams
1986	Chip Science: Basic Study of the Single-Point Cutting Process Topometric Interferometry Advanced Fabrication of Optical Materials
1987	Ductile Grinding of Glass Capacitance Gauges for Contour Measurements Chip Science: A Basic Study of the Single-Point Cutting Process Characterization of X-Ray Optics by Soft X-Ray Diffractometry Electrodeposition of Fe-Ni Alloys Cathodic-Arc Ion Source Precision CNC Controller
1988	Cathodic-Arc Vacuum Processing Chemical Effects During Polishing Development of an Extended Straightness Measurement Reference Interface Tribology by Nonequilibrium Molecular Dynamics Electron Beam Weld Modeling Diamond Turning of Silicon, Glass, and Beryllium Ductile Grinding of Brittle Materials Fabrication of Layered Synthetic Microstructures (LSMs) for X-Ray Optics
1989	Ductile Grinding of Glass Molecular Dynamics Modeling Applied to Indentation and Metal Cutting Problems Cathodic-Arc Process for Thin-Film Coatings Diamond Turning of Optical Single-Crystals Evaluation of Electroformed Copper for Shaped Charge Applications

Table 1, Continued.

FY	Project Titles
1990	Molecular Dynamics Modeling of Indentation and Cutting Ductile Grinding of Glass Coatings from Ions-Modeling and Experiments Preventing Seizure of Sliding-Contact Bearings in Hot, High-Vacuum Environments
1991	Using Electrodeposited Ni-P Coatings to Reduce the Cost of Diamond Turning Tools Molecular Dynamics Modeling of Surface Indentation and Metal Cutting Massively Parallel Computer Simulation of Plane-Strain Elastic-Plastic Flow via Atomistic, Continuum, and Hybrid Mechanics High-Temperature, High-Vacuum Sliding Contact Bearings Increasing Efficiency of Ductile Grinding Large Area Diamond Films Modeling Carbon Films Reduced Coating Defects Laser-Induced Damage Threshold Comparison of Reactive Low Voltage Ion-Plated and e-Beam Coatings Graded Period Multilayer Structures for X-Ray Optics
1992	Fabrication of Amorphous Diamond Coatings Laser-Assisted Self-Sputtering Simulation of Diamond Turning of Copper and Silicon Surfaces
1993	Simulation of Nanometer-Scale Plasticity in Silica Glass Mechanical Characterization of Copper-Diamond Composites
1994	Beryllium-Based Multilayer Mirrors for Normal-Incidence Extreme Ultraviolet Operation Single-Layer Diamond Grinding Wheel High-Speed Lapping of Flat Optics

The magnitude and composition of the *funding* of manufacturing technology developed within the Engineering Department (including Laboratory Directed Research and Development, LDRD) is one indicator of its vitality. Figure 1 shows a profile of the dollars spent specifically in manufacturing development in the year that they were spent. There is abundant manufacturing technology development that is directly funded and conducted by LLNL programs themselves whose funding is not represented in Fig 1. While this component is fundamentally important, it is extremely difficult to track. For example, funding for a new manufacturing effort, the Center for Laser Materials Processing, receives some funding directly from the Laser program, which is not included in Fig. 1, as well as some from institutional R&D (i.e., LDRD), which is included in Fig. 1.

Figure 1. Engineering, LDRD, and CRADA support to manufacturing technology development.

Distinct observations can be made in the funding profile of Fig 1. First, within engineering, manufacturing technology has been substantially internally funded in the past. The concept was to fund an activity until it could stand on its own and begin to contribute to the LLNL programs. Recently, the internal funding has radically diminished. Second, the future need for manufacturing technology must be established, and a target level of activity set that reflects its importance to the programs five to seven years hence. The issue to resolve is whether the reduction in funding results from the general diminution of such discretionary funds or because the technology is becoming less important to the programs.

The next section of this document searches for justification of the thrust area and the level of activity required to make significant contribution to the programs. A target value of 10 FTE, valued at about \$2M, is the critical minimum for a sustained effort and is chosen for the target value for FY00 in Fig. 1. Given

the past funding profile and the justification for future needs, Fig. 1 defines the problem of how to transition from the past to the future. One consequence is that a new activity of the thrust area leader has become to search for funding to supplement that of the thrust area. The shopping for support now actually begins before substantial results are obtained.

1. The evolving funding profile demonstrates that the methods of the past to build/maintain core technology here at LLNL will not serve the future. More specifically, LLNL alone cannot preserve Precision Manufacturing and its capacity to contribute to future programs. Rather, we need to invoke some enduring alliances through which to enhance and preserve the discipline of precision manufacturing.

With respect to its defined activities, the *record of accomplishment* of the thrust area is actually quite good. It is not as though the manufacturing technology thrust area has given rise to a center of activity, as perhaps has the NDE thrust area, but it has certainly promulgated a number of interdependent centers. Superficially, one may ask why the thrust area pushed so heavily on molecular dynamic simulations of fabrication processes. Further investigation reveals that modeling has become an integral characteristic of how we approach many of our problems and has given LLNL a unique and distinct perspective on precision material removal and deposition processes.

Each of these centers has, through EMATT, developed multiple CRADAs with outside industry. By the criteria above, this defines success in that direct funding which succeeds thrust area funding continues to support these centers of activity. Table 2 is a list of the titles of CRADAs in the manufacturing area.

Table 2. CRADA activity in manufacturing technology at LLNL.

CRADA Titles
Deterministic Design of High Precision Slicing Machines
High Precision LVDT Gauge Amplifier
Machine Tool Accuracy Characterization Workshops
Accuracy Enhancement of High Productivity Machine Tools
Transport System for Manufacturing Flat-Panel Displays
Cost Effective Machining of Ceramic Engine Components
Precision Laser Machining and Intelligent Processing Systems
Predictive Model for Heat Treatment Distortion
Intelligent Manufacturing of Commercial Optics
Deterministic Manufacturing of Lithographic Optics
Fixed Abrasive Grinding of Thin Film Recording Heads

2. *There really is a common thread to the majority of the projects in the Thrust Area and as CRADAs; we add precision to a process whether it is in the field of material removal, material deposition, modeling, or metrology. Referring again to Table 1, those titles in bold centrally concerned some aspect precision in manufacturing.*

A relationship between Engineering's R&D and the CRADAs is seen the modified funding profile displayed in Fig. 2 where 50% of the value of the CRADAs in Manufacturing Technology has been added to the funding profile of Fig 1. (Fifty percent was chosen somewhat arbitrarily because CRADA funding supports more than just technology development.) The CRADAs have clearly been used to supplement manufacturing technology development within the Engineering Department. The relationship is however more intricate than just that of funding R&D. One must also note their respective contributions to core competency at LLNL. Core competency comprises two elements: firstly, the existence a knowledge base or a fundamental understanding of a particular technology; and secondly, the ability to apply that knowledge to solve practical problems. Building up core competency overtly absorbs funds long before it covertly generates value. Engineering R&D addresses the first component, that of establishing a knowledge base. The focus of the CRADAs has involved the second component, that of providing applications against which to apply fundamental knowledge and one hopes that along the way he can develop it further.

Figure 2. Engineering and LDRD support to manufacturing technology development.

3. There are two dangers to observe in Fig 2 with respect to the CRADAs. The first is that they are the single largest component in Manufacturing Technology development. The second is that what is being funded through the CRADAs is really the application of technology developed in former times. The CRADAs are selling technology developed over the past ten years and if we don't continue to develop new technology, there will be nothing to tap in the future.

The Future of the Manufacturing Technology Thrust Area

The paramount question is whether the technology advocated by the existing Manufacturing Technology Thrust Area is *critically important* to LLNL five to seven years hence, and whether the technology is so perceived by those who fund it. In answer to the question, one can argue that the four main areas of the past are indeed important to the future of the programs, but they represent

an arena that is too broad to significantly attack with the currently allocated funding (approximately \$0.4M/yr.) and further are not seen as a cohesive and focused effort. The breadth of the existing mission therefore no longer continues to serve the Manufacturing Technology Thrust Area. The narrower focus will henceforth be "precision in manufacturing". The use of "precision" is somewhat ill defined here, but it clearly includes the cost of precision, that is, the purview includes an improvement in the precision-to-cost ratio of manufacturing.

The narrowing of the mission must be *justified*, through engineering, to the programs. The programs include both the traditional programs internal to LLNL and EMATT, representing manufacturing interests outside LLNL. What follows is an attempt show how the narrower focus of the Manufacturing Technology Thrust Area mission makes sense for the future.

There will always be a place for precision manufacturing and engineering as long as LLNL is fundamentally a laboratory where physicists conduct real experiments. Precision engineering lies on the interface between a physicist's "thought" experiment and the real world. Among the many ways to defeat an experiment is if its embodiment lacks the precision to extract fundamental information or if the experiment is too expensive to field. The thrust area's mission of improving precision or precision-to-cost ratio in manufacturing processes attempts to mitigate these. It is this fundamental belief that sustains the Manufacturing Technology Thrust Area through the transition to a new laboratory

It is unclear what role manufacturing in general will play in the future of the DOE. Manufacturing underlies the nuclear weapons component of the DOE mission and is the fundamental reason that precision manufacturing and engineering exists as a core technology at a national laboratory. Indeed, there will be added pressure for this technology as more stringent cost controls are imposed on work at the national labs. This is a supporting reason why the precision-to-cost ratio was included into the scope of the thrust area mission. Adding specificity to the preceding statement has been difficult. While tasks over the next one to two years may be defined, technology development that faces the internal programs in the longer term seems less well defined. If the weapons component of the DOE mission remains strong, so then will the need for precision manufacturing and engineering within the DOE remain strong.

Manufacturing also underlies the newer "industrial competitiveness" component of the DOE mission and has been an active area in the DOE strategic plan. EMATT has helped to define this component of the DOE mission which has given rise to numerous CRADAs in the manufacturing arena between the national labs and US industry. Again, industry has shown great interest in improving the precision-to-cost ratio in their manufacturing processes. Evidence of the key importance of precision manufacturing within the commercial sector abounds in reviewing the success of European and Japanese economies. If the industrial competitiveness component of the DOE mission remains in place, so then will the need for strength in precision manufacturing/engineering remain strong within the DOE.

Manufacturing is clearly delineated in LLNL's vision of its own future as outlined in "Framing the Laboratory's Future" [UCRL-AR-117362, June 1994]. Advanced process and manufacturing technology is indeed called out in this document as one of LLNL's strengths that have application in a range of current and future technical endeavors.

In addition to internal documents like "Framing the Laboratory's Future," several external surveys and reports also help evaluate the importance of precision manufacturing: the DOD Critical Technologies Plan, DOE Defense Critical Technologies Plan, DOE Engineering Initiative, NASA Integrated Technology Plan for the Civil Space Program, Advanced Materials Agenda for the Clinton Administration and the 103rd Congress, and Air Force Materiel Command - FY94 Manufacturing Science and Technology Area Plan.

All of these documents state the importance of precision manufacturing. But, there are hazards in using such surveys to determine which technologies to pursue. First, these reports document a process which has already gone on. As such they are following indicators, not leading indicators of current thinking. The value of these reports derives not from reading them, but from participating in their formulation. Second, these reports can change their orientation quite easily from time to time, they require only republishing. The construction and maintenance of core competency has great inertia and cannot follow the jerky path of a report or collection of reports.

In summary, the information presented in these surveys has very high bandwidth whereas the bandwidth of what the thrust area can effect is very low. Therefore, these reports have been used for corroborating a decision, but not really for making a decision.

The current Precision Engineering Program (PEP) at LLNL is not currently able to fund the development that it has in the past. PEP has derived most of its support from SDIO/BMDO and has not yet been able to augment that funding source. This has left a void in LLNL's ability to plan and execute long term activities in precision engineering at LLNL. In order to fill this void, the thrust area has incorporated precision and precision-to-cost ratio of manufacturing processes into its own mission.

Executing the New Direction of the Manufacturing Technology Thrust Area

There is more than one way to *select the specific areas of activity* in executing the new direction. One is to solicit proposals without bias and wait to see what responses return and then select the best of them. This method has not led to a cohesive Manufacturing Technology Thrust Area and consequently undermines the thrust area's ability to compete well for future funds. This strategy may also be characterized by waiting for opportunities to arise rather than working to a well-conceived plan. The success of such an individual project is of anecdotal importance and may spawn activity in a program, but does not really work to ensure the future of the thrust area.

A second method is to determine what areas in manufacturing will be most important in the future and then try to elicit proposals in those areas. A question is whether to select those areas that correspond well with the strengths of the people at LLNL or to select an area solely because it is important and disregard LLNL's current weakness in the particular technology. One problem with trying to match future needs to existing strengths is that this does not let us look to the future, but only extrapolate the past. Given a list of important activities to pursue, one must be very selective in choosing technologies in which we are not already expert because it is so expensive to bring up a technology compared with just preserving an existing one. Status quo, that is, extrapolating the past has worked well; but the thrust area must change this strategy in order to support programs which themselves are in transition.

Another problem with selecting a technology to pursue in which we are not already expert is that when soliciting proposals in such an area, none are forthcoming. The pre-determined areas of importance and the Manufacturing Technology Thrust Area proposals received in last year's general call were virtually complementary. Therefore, a new procedure was developed where objectives were first outlined for a project which was to be funded and then an engineer was found to champion and carry it forward. Although this method is exceedingly time-consuming, it better supports the thrust area's objective to emerge from the transition in a better position than its competitors; this is a direct consequence of where it spends its development funds and cannot simply be an extrapolation of the past.

The thrust area must serve all the programs. However, beyond being just one of the programs, EMATT enjoys special significance to the Manufacturing Technology Thrust Area in that it is the complement that allows the thrust area to pursue the "dual-use" technologies. The thrust area has generally *selected technologies* that simultaneously address second-tier programmatic problems and significant industrial problems. First tier internally programmatic problems are specifically avoided because they are directly attacked by the programs. Choosing projects that also have outside importance has allowed us to solicit outside funding to supplement internal funding. Over the past two years, the outside funding far outweighed the internal funding. This strategy also attempts to mitigate some of the perturbations to the long range plan that is required to develop an area of expertise. The perturbations may arise from the varying importance of inside Vs outside interests, from the changing popularity of a technology with a single customer, or the vagaries of funding from a single customer. By accommodating both the inside and outside camps, a course can be plotted that has more certainty than one which relies wholly on one customer or set of similar customers.

Activities for FY95 in the Manufacturing Technology Thrust Area

Given the observation that we can no longer independently and wholly sustain precision engineering at LLNL, we will enter into an alliance with UC-Berkeley. It appears that UCB's strengths in manufacturing are quite

complementary to LLNL's in precision and that joining forces will benefit both LLNL and UC. For example, such a union will produce students with an appreciation for precision manufacturing and will have students working on projects of direct interest to LLNL. This alliance will also allow flexibility to perform work where it most makes sense. For example, it is too expensive to do original research at LLNL, so this task may best be apportioned to UC-Berkeley, whereas LLNL will become expert in taking original research and applying it to its own needs. The tasks that will be addressed this year include soliciting high-level endorsement at both institutions for the goals of the alliance and then soliciting financial support for its initiation

We will also maintain our connection with North Carolina State University through our affiliate membership in its Precision Engineering Center. This serves as a method to keep a watchful eye on a university with an active Precision Engineering curriculum as well as to stay informed, through a different perspective, about what problems are currently of concern to industry and academia. It also provides the opportunity for LLNL to influence the direction of research at the PEC/NCSU. Lastly, we will directly incorporate some of the specific research results from the PEC into our efforts here at LLNL, specifically modeling the kinematics of grinding.

As a component of our effort to establish a better connection with academia, we will produce an instructional video showing the application of molecular dynamic simulations to problems in precision engineering. Molecular dynamic simulations are a relatively new tool with which to explore and analyze the limits in precision engineering. Few universities have this capability and hence, few engineering graduates are exposed to this important tool. LLNL has performed a number of such simulations, but they need editing and assembly into a finished video. This video is to be used in US graduate and undergraduate engineering curricula.

With regard to the specific technologies to pursue, the following projects were chosen for FY95 and beyond. The first two are each funded at 25% of the total thrust area funds and the remainder at lesser, "exploratory" levels.

Coated Tools for Precision Turning of Carbide Forming Metals

The overall goals of this project are to machine very smooth surfaces on materials including steel, Titanium and Beryllium; and to do so cost-effectively. Specifically, this will be accomplished through the use of coated tools. An additional payoff is that by adding these metals to the materials that can be precision turned, we can increase the future workload for LLNL's complement of (diamond) turning machines.

A selected few metals (including copper, gold, aluminum and nickel) can be turned with surface roughness less than 5 nm rms through the use of a diamond tool. The high quality workpiece surface results from the very sharp initial edge of the single-crystal diamond and the resistance of the diamond edge to wear against these metals. In contrast, steel, titanium and beryllium cannot be

similarly machined because they cause excessive chemically induced wear of the diamond. However, there is great demand for high quality machining of these latter metals for precision products like dies, ball bearing raceways, aircraft landing structures, scanning mirrors and defense products. Coated tools offer the prospect to combine the initial edge sharpness of the single-crystal diamond with a wear resistant surface against steel, titanium and beryllium.

The first coating strategies taken in this proposal will demonstrate an adherent cBN coating process on a tool substrate. The high temperature strength and stability of a cBN coated tool allow it to maintain edge sharpness while machine steel without a cooling fluid. A secondary benefit of a cBN coated tool is that it may do away with the cost to purchase, handle and dispose of environmentally hazardous fluids after they are spent in the machining process.

The second approach which will be funded by other than thrust area funds, employs a multilayer nano-laminate process suitable for coating a tool. Recent advances in nano-engineered multilayer materials make possible the synthesis of chemically inert, structurally strong, sharp edged cutting tools.

We will coat turning tools and measure their coating thickness and engineering properties including the friction properties and wear resistance of the coating, the adherence of the coating to the tool substrate, the attainable tool edge radius (i.e., the sharpness of the tool). We will then evaluate cutting forces and the life of the tool in a functional test which simulates finish machining.

Precision Saw for Slicing Wafers

The goals of this project are to significantly reduce the cost of manufacturing thin wafers from bulk optical and electronic materials. The embodiment of this proposal is a bandsaw that incorporates both new blade technology and novel machine design. The advantages of this bandsaw arise because, as a system, it pushes the very first machining operation, slicing, from a roughing process to a semi-finishing operation.

Materials from which wafers are cut include optical and electronic materials in boule form such as KDP, GaAs, and silicon. The initial operation in manufacturing wafers from boules is the slicing process. Slicing currently suffers from its inability to produce flat surfaces free from sub-surface damage while maintaining long blade life and small kerf. The significant penalty associated with this process derives not from the cost of the sawing operation, but from the cost of subsequent fabrication processes to remove damage and to planarize the surface and which are made necessary by the sawing operation.

A new precision, fixed-abrasive bandsaw is proposed as a replacement for the current generation of saws. The specific advantages of this saw are long blade life, small kerf, reduced subsurface damage by cutting in the shear mode and good control of surface flatness. Cost reduction is realized because a number of the subsequent manufacturing operations such as lapping or turning can be reduced or eliminated. Cost reduction is also realized because waste disposal (consider for example, gallium arsenide) is reduced by the small kerf. In addition, more slabs are available from a single boule.

Precision Issues in Hard X-Ray Imaging Telescopes

The overall objective is to develop fabrication and assembly processes for the reflecting elements of an astronomic telescope imaging system to be used in the hard X-ray regime. The specific objective for this project is to demonstrate a cost-effective structural form that minimizes obscuration and also allows economic assembly and alignment. In addition, the design must withstand severe force and perhaps thermal loads before use and then function in a service environment that is subject to the same such perturbations, but less severe.

Imaging in the hard X-ray regime has been identified by the Physics directorate as one of their thrust areas of fundamental, long term interest. Two different concepts for telescopes operating in this regime will, for example, be proposed to NASA as technologies to pursue for imaging. One of these two technologies is a telescope comprising many nested, low-cost, reflective optical elements. The challenge in precision manufacturing arises because each of the fifty or so elements composing a telescope is a very thin reflective shell that must be fabricated to a specified optical form and then aligned with respect to the others.

The future of these telescopes lies in their lower cost and their ability to be fielded on lower cost platforms. Whether and how many of these telescopes are fielded is therefore not an issue of physics, but rather one of performance-to-cost ratio. The cost drivers appear to be in the fabrication of a shell and, in its assembly and alignment.

Conclusion

The specific mission of the thrust area will continue to evolve and, depending on future funding, may again broaden from its current narrow scope. It is clear that precision has always been and will probably always be a staple of the thrust area. Further thought needs to be given to some aspects glossed over in this document. These include:

1. How to show the relationship of manufacturing technology development as funded directly by the programs (not really discussed here) and that funded through Engineering (the subject of this document). It is the component funded directly by the programs that defines the environment in which the Manufacturing Technology Thrust Area operates.
2. How to quantify a precision-to-cost ratio, perhaps for different industries or products, and then identify what level of precision-to-cost is necessary to make significant advances in that industry or product.
3. What level of activity makes sense for a "healthy" effort?