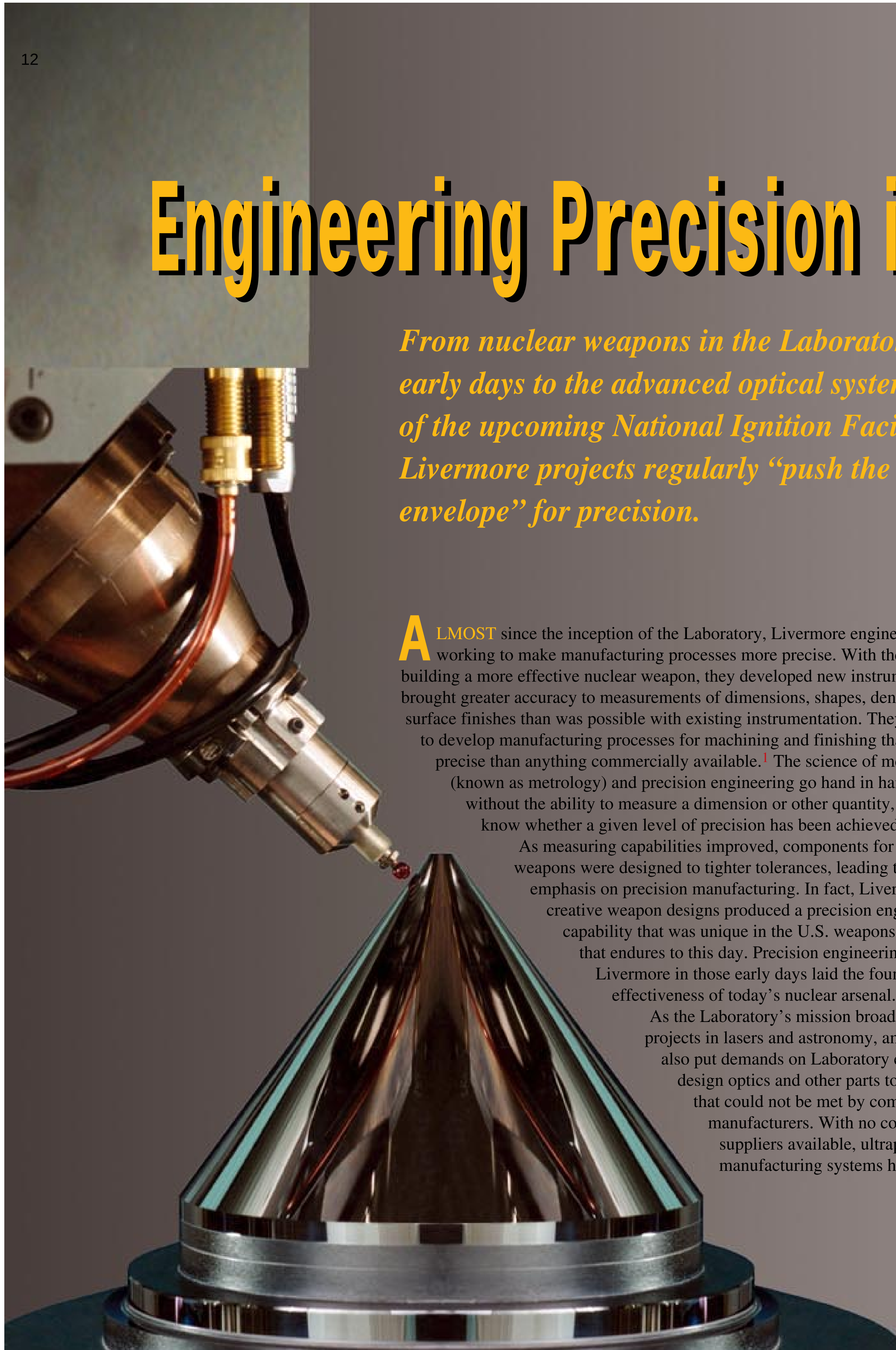
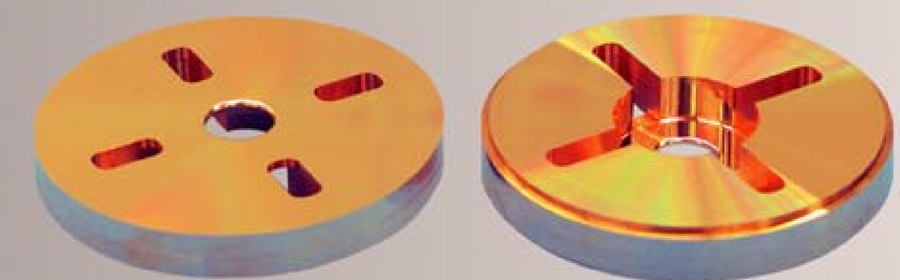


Engineering Precision into Laboratory Projects

From nuclear weapons in the Laboratory's early days to the advanced optical systems of the upcoming National Ignition Facility, Livermore projects regularly "push the envelope" for precision.



ALMOST since the inception of the Laboratory, Livermore engineers have been working to make manufacturing processes more precise. With the goal of building a more effective nuclear weapon, they developed new instruments that brought greater accuracy to measurements of dimensions, shapes, densities, and surface finishes than was possible with existing instrumentation. They also worked to develop manufacturing processes for machining and finishing that were more precise than anything commercially available.[1] The science of measurement (known as metrology) and precision engineering go hand in hand, because without the ability to measure a dimension or other quantity, one can never know whether a given level of precision has been achieved.

As measuring capabilities improved, components for nuclear weapons were designed to tighter tolerances, leading to an increased emphasis on precision manufacturing. In fact, Livermore's creative weapon designs produced a precision engineering capability that was unique in the U.S. weapons complex and that endures to this day. Precision engineering at Livermore in those early days laid the foundation for the effectiveness of today's nuclear arsenal.

As the Laboratory's mission broadened in scope, projects in lasers and astronomy, among others, also put demands on Laboratory engineers to design optics and other parts to tolerances that could not be met by commercial manufacturers. With no commercial suppliers available, ultraprecise manufacturing systems had to be developed, many of which were later transferred to the private sector. Today, the Laboratory would have no difficulty commercially obtaining many of the instruments and manufacturing systems it developed as prototypes 10 years ago. But the demand for precision at the Laboratory continues to increase, keeping Livermore's precision engineers busy.

Livermore scientists do not shy away from projects that require precision. The National Ignition Facility (NIF), which is now under construction, is perhaps the premier example. Upon completion, NIF will be the world's largest laser and most sophisticated optical instrument, with over 7,500 high-precision optical components larger than 40 centimeters in diameter, including amplifier slabs, lenses, mirrors, polarizers, crystals, windows, and shields. It will also incorporate more than 40,000 smaller optical components. Lawrence Livermore is one of the few organizations in the world with the capabilities necessary to execute a project requiring the level of precision demanded by NIF. As Laboratory Director Bruce Tarter said in a speech at a recent symposium on precision manufacturing, "Precision engineering is on LLNL's short list of core competencies." It has been for 40 years and probably always will be. And today, it is one of the capabilities helping to make the National Ignition Facility a reality.

Pioneers in Precision

Livermore was a pioneer when it started its work in precision engineering in the 1950s. Private industry did not then have the economic incentive to carry out the necessary developmental work. Today, many commercial firms are concerned with conforming to tight tolerances and specify that their manufacturing machinery be designed accordingly. But they seldom have the analytical skills needed to both improve the precision of their manufacturing processes and embody that improvement in the design of their machinery.

As one of just a few organizations in the world that combines expertise in both process development and machine design, Lawrence Livermore brings something unique to the precision engineering table. Livermore has an in-depth understanding of physical phenomena, equipment, and processes and employs this understanding in both developmental work and practical applications.

Livermore's precision engineers tend to be generalists who attack a whole problem rather than specialists who work only on one aspect of it. At Livermore, precision engineers take a systems view of how to gain higher precision—or high precision for less cost—than is currently possible. Many disciplines work together to meet the demands of Laboratory programs.

As experts in dimensional metrology, machine design, and material removal processes, Livermore's precision engineers have developed an impressive array of state-of-the-art tools, some of which are described in the box on pp. 16–17.

Greater Precision for Less

Much of today's precision engineering work reflects a change in philosophy that first appeared some 15 years ago. Absolute accuracy used to be the objective. But as cost has become a greater factor in most projects, the goal has changed to one of constantly improving the precision-to-cost ratio.

Meeting NIF Challenges

This new goal is perhaps nowhere more important than at the National Ignition Facility where the cost of all components must be about one-third of today's typical cost, with precision and tolerances equal to or exceeding present capabilities.

One of the critical precision engineering tasks for NIF is the development of new manufacturing processes that will be used by commercial vendors to machine KDP (potassium dihydrogen phosphate) crystals for NIF's laser system. KDP crystals are also used in the Nova laser and are produced by a commercial supplier, but NIF's tighter tolerances call for the KDP to have a surface quality higher than that currently available commercially (Figure 1).

Figure 1. Large KDP (potassium dihydrogen phosphate) crystals, such as the one shown here in its final optical mount, will be used in the National Ignition Facility. Precision engineers at Livermore have developed the methods for machining these crystals to NIF tolerances. They are also developing an instrument to ensure that the crystals are manufactured to specification and are aligned so they will function properly within the NIF laser.

Several years ago, Livermore scientists won an R&D 100 Award for a method to accelerate the growth of KDP crystals.[2] Livermore precision engineers are developing methods for machining these new crystals to NIF tolerances. They have modified a Laboratory machine for initial rough cutting of the crystals and have shipped it to the vendor who will produce the crystals. They have also developed a process for crystal finishing and have written the specifications for the finishing machine. During 1998, the vendor will assemble the finishing machine at the Livermore site. The best news is that the best way to manufacture the crystals to specified tolerances meets NIF's cost requirements.

Livermore is also developing the instrument that will be used to align the crystals. Known as Crystal Alignment and Verification Equipment (CAVE), this tool ensures not only that the crystals are manufactured to specification but also that they are properly aligned and function in accordance with the specification.

Improved Accelerator Cells

Cost is also a major issue for a new linear electron–positron collider for basic physics research that is currently in the developmental stage. Lawrence Livermore has teamed with the Stanford Linear Accelerator Center and Lawrence Berkeley National Laboratory on its design, which calls for 1.9 million accelerator cells designed to submicrometer tolerances.

In the current baseline design, groups of 204 cells are bonded into 1.8-meter-long structures. To improve accelerator performance, these cells are designed to vary gradually over the length of each structure. Ninety-two hundred of these structures are to be installed and aligned over the 21 kilometers of the beamline.

Manufacturers of high-end optics could supply these parts, but the cost would be unacceptably high. In an effort to reduce the current estimated cost, Livermore precision engineers are exploring less expensive alternatives for manufacturing these components (Figure 2), including developing prototypical manufacturing processes. Many trade-offs are being considered to minimize cost while achieving the required accelerator performance in a reasonable fabrication time. The project manufacturing plan will be part of the conceptual design report that will demonstrate why this new collider should be built.

System Development

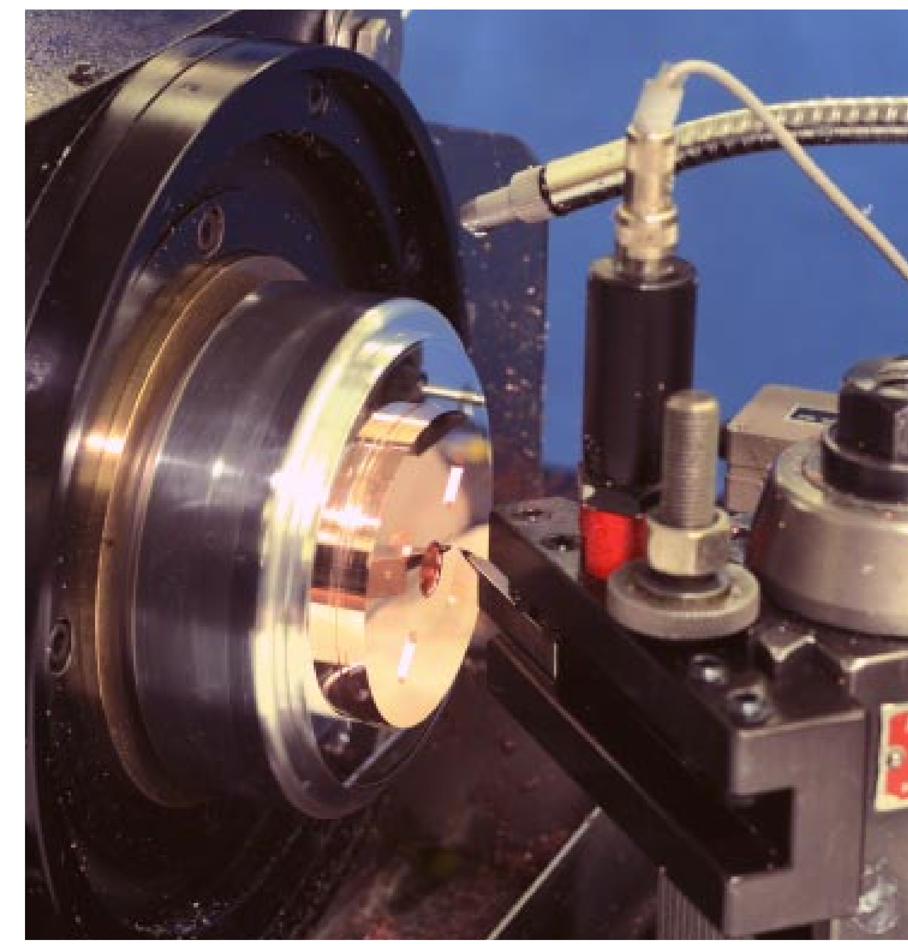
Precision engineering requires, among other things, a systematic approach to determining dimensional errors. When measurements are made, precision engineering requires a quantitative assessment of the total uncertainty of the measurement. During the manufacture of a component, it requires an "error budget"—a comprehensive estimate of what errors may affect the tolerances of the component. Meeting these requirements means that the Laboratory's precision engineers must become good at system integration. Two examples where precision engineering has been integrated into Laboratory projects are advances in extreme ultraviolet (EUV) lithography for printing computer chips and the development of a workstation for the femtosecond laser cutter.

Measuring Optical Surface Errors

Earlier Laboratory work on multilayer reflective coatings for inertial confinement fusion produced part of the technology that has enabled development of EUV lithography for printing computer chips. With this technology, computer chips will be 100 times faster and able to store 1,000 times more information than those made using current lithographic methods. To meet these performance demands, the next generation of computer chips must have circuit line widths that are 0.1 micrometer or less. The manufacturing process for these chips will obviously demand extremely tight tolerances.

EUV lithography uses laser light with a very short wavelength—shorter than ultraviolet but longer than x ray—to project the circuit pattern by reflection onto each chip. The system that can do this requires mirrors, cameras, and other devices with some of the most accurate optics ever made. Thus, developing EUV lithography is essentially an exercise in precision

Figure 2. A prototype accelerator cell being machined to submicrometer tolerances by a small diamond-turning machine at Livermore for the proposed new electron–positron collider at the Stanford Linear Accelerator Center in Menlo Park, California. The collider will require almost 1.9 million of these cells, and Lawrence Livermore is developing a manufacturing plan for minimizing fabrication costs.



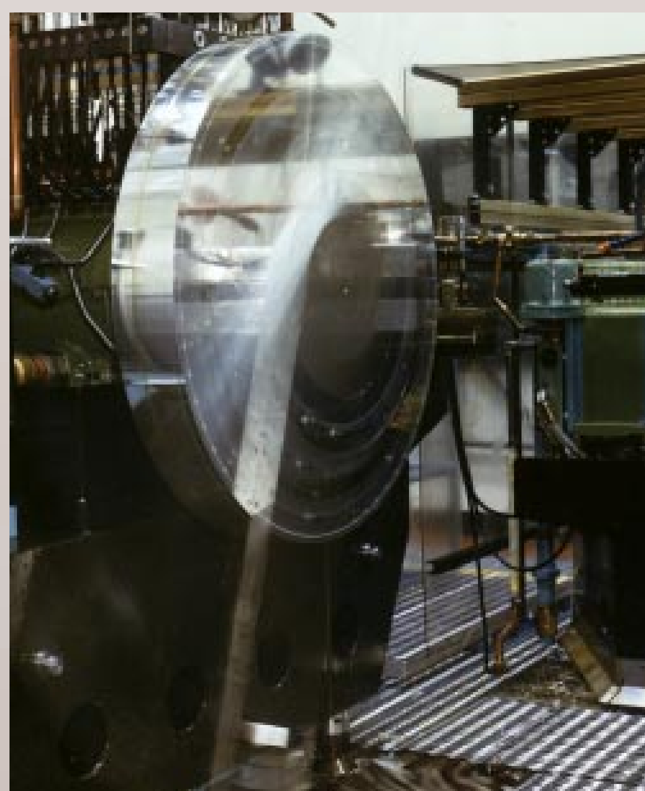
Metrology and Machining at Livermore

Advances in Metrology

Livermore has invented a number of new metrological devices in response to programs that have needed parts fabricated or measurements made beyond the limits of existing instruments. Several of them have won R&D 100 (earlier known as IR 100) awards, and many have been commercialized. These include the laser heterodyne profiler, developed in the 1970s, and an amplifier to increase the resolution of a linear variable differential transformer (LVDT), which was developed in 1990 with Lion Precision of St. Paul, Minnesota.* Both of these tools are used to measure errors in the surface of optical elements such as mirrors and lenses.

A recent invention takes the measurement of optical errors to the atomic level for the first time. The absolute interferometer, shown in Figure 3 on p. 18, produces measurements of optical surfaces to within just one or two atoms, or less than 1 nanometer.**

In the early 1980s, Livermore scientists combined an LVDT with a hydrostatic spindle and a computer. Called the Compuron, this tool can measure the roundness of parts with an accuracy of 2.5 nanometers and is still in use today at Livermore.



Diamond-turning machine 3 (DTM3) is large enough to machine a cylinder 2.1 meters (84 inches) in diameter by 1.1 meters (44 inches) long. DTM3 is kept at a constant temperature by a shower of light machine oil that flows at 400 gallons per minute. The horizontal *x* axis carries the spindle, which holds the part, and the *z* axis carries the tool perpendicular to the part. DTM3 has been used to produce many types of optical surfaces.

Metrology tools find many uses. The most obvious is to measure shape errors in the part being produced. But they also can measure the errors arising in the equipment used to manufacture the part, a practice known as machine tool metrology. And they are often used to measure a process—for example, to characterize a grinding wheel.

Livermore has also continually supported the development of standards that are important to precision engineering. Most of this work has been with the American Society of Mechanical Engineers and American National Standards Institute in such areas as surface texture, dimensional measurement, measurement procedures for acceptance testing of machine tools, and symbology and tolerances for drawings. Livermore scientists are also active in working with the International Standards Organization to establish international metrological standards.

An example of the importance of standards arises in what seems at first to be a simple operation—measuring the dimensions of an object. Because temperature affects an object's shape, lengths are, by international agreement, specified at 20°C. But few such measurements are performed at exactly that temperature, so engineers use an equation that considers the coefficient of thermal expansion of the part's material to describe the change in length. Even then, errors may occur if the length measurement at ambient temperature is not made carefully or if the temperature difference from 20°C is determined incorrectly. If a seller and a buyer of a component perform the calculation differently, they will compute different lengths for the part. Thus, the procedures for assessing length must be carefully prescribed so that all parties get the same result.

Designing High-Precision Machines

At the same time that Livermore scientists were improving the science of metrology, they were also making major advances in developing high-precision machining tools.

A key ingredient in the design of any precision machine is the error budget, which delineates how much uncertainty or nonrepeatability can be tolerated at each step in the production process. Predictability and repeatability must be maximized in these machines if they are to consistently produce parts with tolerances of fractions of a micrometer.

Most of the machine tools that Livermore has developed are for turning, primarily diamond turning, but advances have also been made in grinding. Turning is a point-defined process that draws a single tool across a surface in a highly controlled manner. Grinding is an area-averaging process that moves tiny abrasive particles across a surface in a less predictable manner. Turning excels in producing precise size and contour, whereas grinding can produce a smooth surface finish on selected materials.

Since the 1960s, Livermore has continually experimented with and refined the science of diamond turning, which uses a specially designed precision lathe and a single-crystal diamond tool to machine metals to a mirror-like finish and extremely close dimensional tolerances. Livermore designed and produced several large diamond-turning machines, each with greater contour accuracy than its predecessor. Most designs incorporate fluid bearings of either air or oil to reduce friction and increase stiffness, strict temperature control, and as much vibration isolation as possible. (See figure on p. 16.)

One of the finest achievements of precision engineering at Livermore is the Large Optics Diamond Turning Machine (LODTM, pronounced "loddem"), the world's most accurate machine tool. (See figure at right.) Built in the early 1980s to machine prototype large-diameter mirrors made of copper, electroless nickel, and other metals for the Department of Defense, LODTM can machine workpieces as large as 1.5 meters (5 feet) in diameter and 46 centimeters (18 inches) in height to an accuracy of greater than 30 nanometers rms (root mean square). LODTM has also been used to produce secondary mirrors for the Keck Observatory in Hawaii and continues to be used to develop prototype optics.

Diamond turning is ideal for machining certain nonferrous metals such as copper, gold, aluminum, and nickel. Livermore has extended its use to machining of such brittle materials as the nonlinear crystal KDP (potassium dihydrogen phosphate), which is used in the Nova laser and the upcoming National Ignition Facility. The Laboratory is also evaluating diamond turning for the finishing of silicon as a mirror substrate for high-energy lasers.

But some materials, including steel, titanium, and beryllium, react chemically with the diamond point, causing it to wear excessively. Livermore has experimented with single-crystal cubic boron nitride (cBN), which is stable and strong to high temperatures, as an alternative to a diamond tool, but early trials have shown that single-crystal cBN is too delicate for use in machining. Instead, we are developing turning tools that are diamond with coatings of cBN and other hard materials, which allow the tool to maintain its sharp edge.

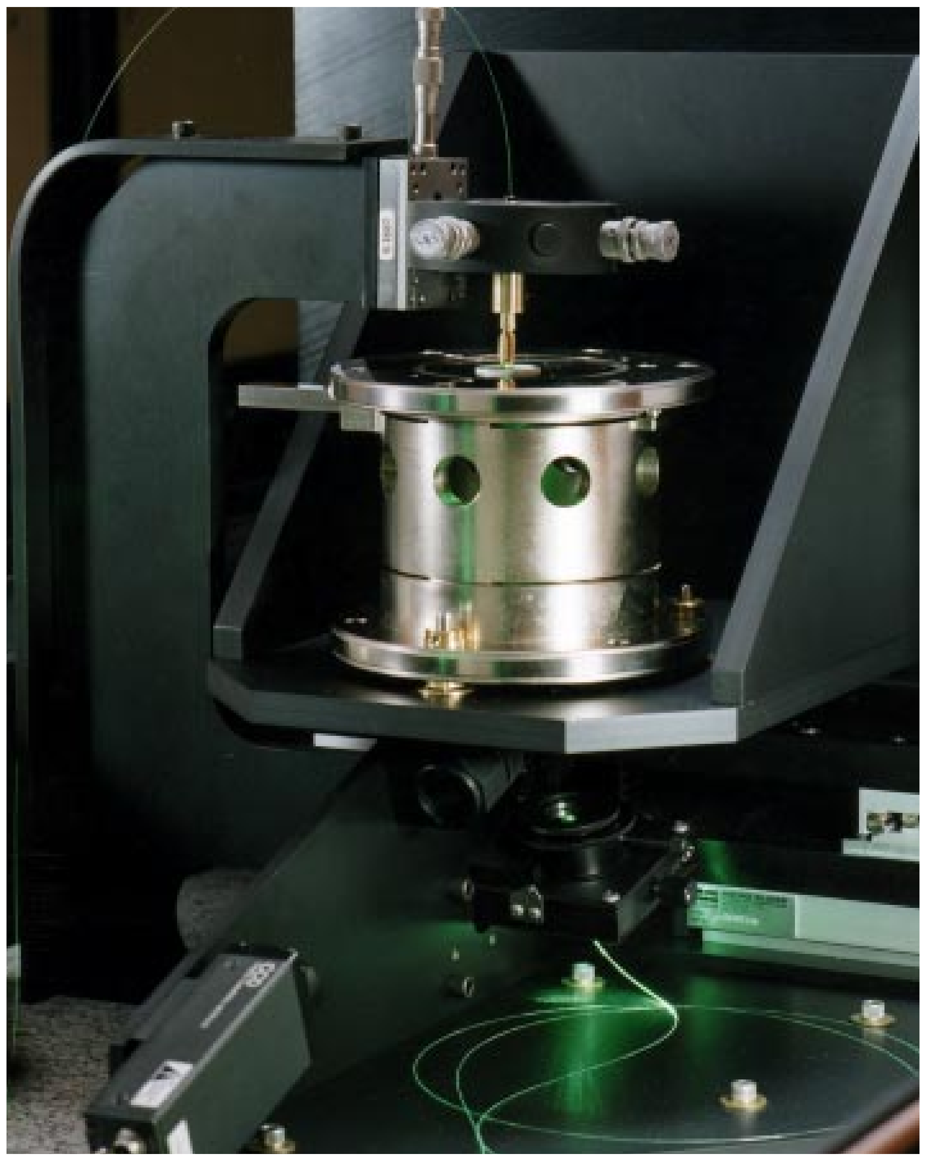
Ductile grinding emerged in the 1980s as a possible analog to diamond turning for finishing ceramics, glass, and other brittle materials. It differs from other types of grinding in that the surface being ground is smeared rather than cracked. The process uses an extremely fine grit (less than 20 nanometers) and requires careful control of the force of the grit to minimize its penetration into the surface. An acoustic-emission sensing system developed at Livermore assists with controlling the process by detecting the proximity of the grinding wheel to the workpiece and supplying in-process measurements for monitoring grinding quality. Still under development at Livermore and elsewhere, ductile grinding produces a finer, higher quality finish than ordinary grinding. In glass, for example, grinding typically produces a frosty surface, but ductile grinding produces a shiny surface.

*"High-Precision Low-Noise LVDT Amplifier," *Energy & Technology Review*, Lawrence Livermore National Laboratory, Livermore, California, UCRL-52000-94-11 (November 1994), pp. 6–7.

**"New Interferometer Measures to Atomic Dimensions," *Science & Technology Review*, Lawrence Livermore National Laboratory, Livermore, California, UCRL-52000-97-10 (October 1997), pp. 6–7.

The Large Optics Diamond Turning Machine (LODTM) machining a workpiece. Many of the LODTM's parts are made of a special steel alloy (Super Invar), which has an exceptionally low coefficient of thermal expansion. Air cooling for the area around the machine keeps temperature changes to within about 10 millidegrees Celsius, and a water cooling system for the metrology system keeps changes to less than 1 millidegree over a day.

Figure 3. Developed at Livermore and winner of a 1997 R&D 100 Award, the absolute interferometer can measure errors in the surfaces of optical parts to the thickness of just a few atoms. This metrological exactness is helping to make possible the next generation of high-power computer chips, produced using extreme ultraviolet lithography.



engineering. For example, the surface of the optical parts in the camera must be accurate to within just a few atoms, because the smoothness of the surface finish determines how much of the light will be scattered and lost. Less scatter translates into a shorter exposure time for each chip and a higher production rate. The overall shape of the optical surface must also be accurate to improve the accuracy with which the pattern is projected.

Existing metrology could not measure surface shape with sufficient precision, so Livermore developed the absolute interferometer, which can measure errors of a surface to just a few atoms (Figure 3).[3] This new ability to measure surfaces of optical parts to the required tolerances removes one of the roadblocks to further development of EUV lithography.

Exploiting Laser Cutter's Precision

In another project, Livermore engineers are developing a workstation for the femtosecond laser cutter, a breakthrough manufacturing process that also spun off from inertial confinement fusion work. This laser cutter delivers pulses lasting just 50 to 1,000 femtoseconds (quadrillionths of a second), ionizing the material and removing it atom by atom. The precision engineer's job was to design and construct a machine tool to a precision that can exploit the femtosecond laser's capabilities to cut materials, whether they be steel or soft tissue, very exactly and with little or no collateral damage. In the workstation, ultrasonic sensor technology is used to locate and mark the cut. The cutting takes place in a vacuum chamber with diagnostic cameras measuring the cut.

The cutter's first application was to disassemble nuclear weapons at DOE's Pantex plant.[4] Several major manufacturers are interested in incorporating this new cutter into their manufacturing process. With the workstation, this precision cutting technology can make the move to industry.

The Impact of Precision

The precision work at Lawrence Livermore has had an impact not only on the Laboratory itself, but also on everyday products. Because so many precision manufacturing methods developed at Livermore have been transferred to the private sector, companies and individuals outside Lawrence Livermore can obtain many machines, parts, and materials of a higher quality and at a lower cost than was previously possible.

An example of Livermore's effect on the private sector involves the diamond turning of infrared optical components for heat-seeking missiles. Because the Department of Defense wanted to be able to obtain the components commercially, it paid Livermore to transfer the diamond-turning technology to the private sector in the early 1980s. The technology that produced those components was the forebearer of the methods used today to produce precision components for bar-code scanners, video cassette recorders, compact disc players, laser printers, and copy machines.

A few breakthrough technologies, such as the laser interferometer and the personal computer, have revolutionized how machines are designed, but most advances in precision engineering today are incremental. This in no way dilutes their importance, however. It has been estimated, for instance, that modest improvements in the accuracy of fabricating the skins and spars for a Boeing 747 jet would reduce the weight of the aircraft by 10,000 pounds. If those minimal changes were made to all 747s in use today, the net result would be a fuel cost savings of about $600 million every year for U.S. airlines.

Precision manufacturing is also expected to reduce hydrocarbon emissions from combustion engines. Figure 4 shows how these emissions were reduced from 3.2 grams per mile to 0.9 gram per mile when the catalytic converter was introduced in the mid-1970s and then to about 0.4 gram per mile when electronic controls were added. With present engine designs and manufacturing technologies, automobile manufacturers cannot meet demanding new emission standards. But the same manufacturers predict that new combustion chamber designs using precision engineering technologies will drive the next major advance in emissions reduction.

A Leader in the Field

Although precision engineering has been a core competency at Livermore Laboratory for four decades, it was not a cohesive discipline in the U.S. private sector until about 20 years ago. Livermore's long-standing leadership in the field of precision engineering has prompted it to take a leading role in broadening the recognition and application of the discipline. In the mid-1980s, several Livermore engineers helped to establish the American Society for Precision Engineering, which has become an active international organization, with more than 700 members from industry, universities, and government.

Today, precision engineering is a recognized technology that is used regularly to respond to a range of challenges. The Laboratory, manufacturers, and others are relying increasingly on precision engineering to meet future demands and reduce costs.

Precision engineering will have a place at Livermore as long as physics experimentation continues. Physics experiments cry out for perfection. While perfection is seldom possible in an engineered system, increasing the system's precision brings it as close to perfection as possible.

—Katie Walter

Key Words: diamond turning, extreme ultraviolet (EUV) lithography, femtosecond laser cutter, KDP (potassium dihydrogen phosphate), Large Optics Diamond Turning Machine (LODTM), machine design,

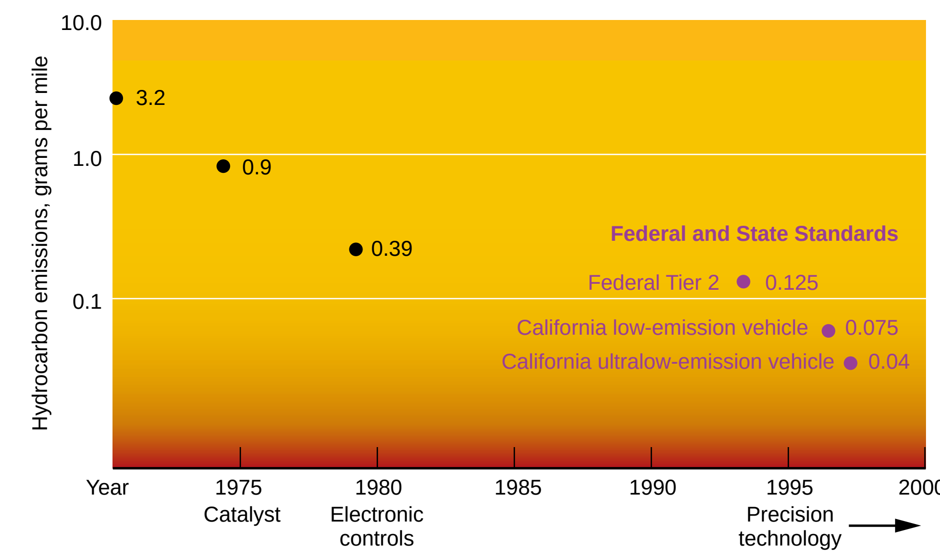


Figure 4. The use of precision engineering in the manufacture of internal combustion engines is expected to reduce hydrocarbon emissions to levels that meet new federal and state standards.

National Ignition Facility (NIF), optical systems, precision engineering, process development.

References

1. For more information on the early days of precision engineering at Livermore, see articles in *Energy & Technology Review*, Lawrence Livermore National Laboratory, Livermore, California, UCRL-52000-87-9 (September 1987). Many of the advances in precision metrology discussed in these articles have become commercial instruments.
2. See “Growing High-Quality KDP Crystals Quickly,” *Energy & Technology Review*, Lawrence Livermore National Laboratory, Livermore, California, UCRL-52000-94-11 (November 1994), pp. 3–5.
3. “New Interferometer Measures to Atomic Dimension,” *Science & Technology Review*, Lawrence Livermore National Laboratory, Livermore, California, UCRL-52000-97-10 (October 1997), pp. 6–7.
4. See “A New Precision Cutting Tool: The Femtosecond Laser,” *Science & Technology Review*, Lawrence Livermore National Laboratory, Livermore, California, UCRL-52000-97-10 (October 1997), pp. 10–11.

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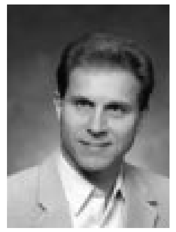
About the Precision Engineers



KENNETH BLAEDEL is leader of the Precision Systems and Manufacturing Group (formerly the Machine Tool Development Group), part of the Engineering Directorate’s Manufacturing and Materials Engineering Division at Lawrence Livermore. He is a specialist in material removal processes, particularly the grinding of brittle materials, and in the design of machines to conduct these processes. He has been involved in the design and application of many of the precision diamond-turning machines at the Laboratory. He holds both a B.S. and Ph.D. in mechanical engineering from the University of Wisconsin and is an active member of the American Society for Precision Engineering. He has extensive experience in dimensional metrology and currently chairs the Environment for Dimensional Measurement Committee for the American Society of Mechanical Engineers/American National Standards Institute.

DANIEL THOMPSON has been associated with precision engineering at Livermore since joining the Laboratory in 1975. He is currently Program Leader for the Energy Directorate’s Precision Engineering Program and previously led Livermore’s Machine Tool Development Group for 11 years. He received a B.S. in mathematics from the University of Colorado and an M.E. in mechanical engineering from the Thayer School of Engineering at Dartmouth College. He is past president of the American Society for Precision Engineering and serves as associate editor for *Precision Engineering*. He received the Federal Laboratory Consortium award for excellence in technology transfer and has received two IR-100 (now R&D 100) awards for developments in precision engineering.

Enhanced Surveillance of Aging Weapons

Figure 1. The relative size of the vacuum-tight microextractor assembly (left) and the coated microextraction fiber (right) compared to a quarter. The fiber is less than 400 micrometers in diameter.

WITHIN the Department of Energy, the word “surveillance” has a meaning closely akin to the word from which it derives—“vigilance.” For years, the DOE has had an ongoing surveillance program to verify the safety and reliability of U.S. nuclear weapons. Surveillance has always dealt with the possible effects that aging may have on weapon materials and components. The study of aging effects is even more important now that nuclear testing has ceased, no new weapons are being developed, and the existing arsenal is growing older. Current plans call for many of the weapon systems in the arsenal to be in the stockpile well beyond their design lifetimes, and scientists must be able to predict the behavior of these systems as they age.

DOE’s enhanced surveillance program is just one facet of science-based stockpile stewardship.[1] Since the program began in 1995, it has been managed by DOE’s Office of Defense Programs. But the work is actually being done by the seven DOE facilities that designed and fabricated the weapons in the first place—Livermore, Los Alamos, and Sandia national laboratories as well as the Y-12, Kansas City, Pantex, and Savannah River plants.

The objective of the enhanced surveillance program is to develop diagnostic tools and predictive models that will make it possible to analyze and predict the effects that aging may have on weapon materials, components, and systems. With this information, program participants will be able to determine if and when these possible effects will impact weapon reliability, safety, or performance and thus will be able to anticipate needs for weapon refurbishment. Because the DOE weapons complex has been reduced in numbers of plants and personnel, the lead time necessary to manufacture critical components must be as long as is practical. Enhanced surveillance is crucial to providing the longest lead time the DOE complex can afford to provide.

Specifically, the program’s goals are to predict component and material failure mechanisms; predict the service lives of materials, components, and overall systems; determine the feasibility of monitoring critical components in place, in real time, nondestructively; and develop diagnostics for failure mechanisms when time to failure cannot be adequately predicted.

Surveillance of Thermonuclear Weapons

The seven participating facilities are working on 110 tasks in three focus areas: primaries, secondaries, and nonnuclear components. Livermore has only minor involvement with project work related to nonnuclear components, which is Sandia’s specialty. However, the Laboratory is heavily involved in the first two areas because its specialty has always been the development of primaries and secondaries, where the fission and fusion processes occur in a thermonuclear weapon. For the work at Livermore, Jeffrey Kass and John Kolb are leading a multidisciplinary team that includes physicists, engineers, materials specialists, and technicians from several directorates.

For weapon primaries, the Livermore team is evaluating changes that occur over time to the pit’s special nuclear materials and to various types of high explosives. For example, plutonium irradiates itself and, given enough time, may change shape ever so slightly. Other tasks involve developing sensors, imaging devices, and diagnostic techniques for nondestructive evaluation of a primary. The team is also developing methods for studying the dynamic properties of primaries through small-scale testing.

Similar work is under way for weapon secondaries, characterizing materials in detail and developing material aging models to predict material life. Livermore staff are also