program), were used as reference points for adjusting model parameters.

Simulations were performed to separately assess the changes caused by (1) land clearing and fossil-fuel burning, (2) land clearing only, (3) fossil-fuel burning only, and (4) both plus observed atmospheric data until 1990, which includes nuclear-testing ^{14}C levels. The last simulation indicates the model's ability to portray past trends and predict future ^{14}C fluxes.

The simulations indicate what percentages of increases in atmospheric CO_2 can be attributed to deforestation and fossil-fuel burning. The data indicate that, prior to about 1910, most of the carbon entering the ocean resulted from deforestation; since that date, the carbon flux has been dominated by the effects of fossil-fuel burning.

The modelers' interpretation of the trends led them to the unexpected prediction that ^{14}C levels in the atmosphere will begin to increase as a result of fossil-fuel burning. The modelers explain it this way: When atmospheric CO_2 content increases, the ocean's absorption of it increases. In the case of fossil-fuel-caused increases, because fossil fuel contains no radiocarbon, the ocean is absorbing CO_2 that consists primarily of ^{12}C, a weak acid. A more acidic ocean tends to reject carbon in all its isotopic forms. So the ^{14}C component of ocean CO_2 is rejected along with the other carbon isotopes, adding to the atmospheric ^{14}C content and reversing the decline that began in the 1960s after the end of atmospheric testing. The model indicates that ^{14}C levels will begin increasing as early as 1998 and, by 2015, the fossil-fuel-induced radiocarbon flux out of the ocean will exceed the nuclear-explosion radiocarbon flux into the ocean, so the ocean's ^{14}C mass will then begin to diminish.

The Caldeira, Duffy, and Rau model is noteworthy because the prediction that the ^{14}C flux into the ocean will be reversed early in the next century indicates that human impacts on the global carbon cycle are significant on geologic, not just human, time scales.

Closing In on Global Climate

The growing consensus that fossil-fuel use is causing climate change and the recent effort to formulate international treaties to limit greenhouse-gas emissions lend urgency to understanding how carbon moves within the climate system. If indeed humans have been responsible for changing the climate, climate models must accurately and conclusively portray this cause and effect. Then we will have the understanding needed to begin mitigating the effects and assuring a better future for the environment.

—*Gloria Wilt*

Key Words: carbon cycle, carbon dioxide (CO_2), climate change, climate model, fossil-fuel burning, global warming, greenhouse gas, marine biology, mass spectrometry, ocean carbon cycle, ocean convection, proxy data, radiocarbon (^{14}C).

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About the Scientists

PHILIP B. DUFFY is a physicist at the Laboratory, where he is group leader for the Climate System Modeling Group in the Atmospheric Science Division. Duffy worked in strategic defense systems when he joined the Laboratory in 1986. Prior to that, he received his Ph.D. and M.S. in astrophysics in 1986 and 1981 from Stanford University and an A.B. in astronomy and astrophysics in 1979 from Harvard University. Duffy has published research on astronomy, atomic physics, and numerical modeling of ocean circulation.

KENNETH G. CALDEIRA joined the Laboratory's Atmospheric Chemistry Group as a physicist in 1993 and has been an environmental scientist in the Climate System Modeling Group since 1995. He received his Ph.D. and M.S. in atmospheric science from New York University in 1991 and 1988 and his B.A. in philosophy from Rutgers University in 1978. He also served as a postdoc at Pennsylvania State University's Earth System Science Center. Caldeira has published many papers, for example, on climate stability of early Earth and the global carbon cycle as it has been affected by human activity over millions of years.

Reliable Software for Protection Systems

A patient undergoing radiation therapy for cancer wants to be sure that the radiation being delivered is just the amount prescribed and no more. Nuclear power plants must have systems installed to ensure that radiation leaks and accidents do not occur. Today, controlling these protection systems flawlessly depends upon computer software, which occasionally contains unforeseen "bugs." Software bugs on your computer at home are annoying, but at a nuclear power plant or during radiation therapy they can be life-threatening.

At Lawrence Livermore, Gary Johnson's Computer Safety and Reliability Group—part of the Fission Energy and Systems Safety Program—has been working with the Nuclear Regulatory Commission for several years to avoid software problems in safety systems at nuclear power plants. Livermore brings to this job decades of systems engineering experience as well as a regulatory perspective from years of working with the NRC and other regulators.

Johnson's group and the NRC developed software and computer system design guidance that the NRC uses to evaluate the design of safety-critical systems for U.S. plant retrofits. Overseas, where new nuclear power plants are being built, regulators and designers are using this state-of-the-art guidance to help assure plant safety. For the last few years, representatives from Hungary, the Czech Republic, Ukraine, Korea, Taiwan, and Japan have been calling upon Johnson and his group for assistance in setting criteria for their nuclear power plant control systems.

This software design guidance is also applicable to other computer-controlled systems that could endanger human life if they are poorly designed—medical radiation machines, aircraft flight control systems, and railroad signals, for example.

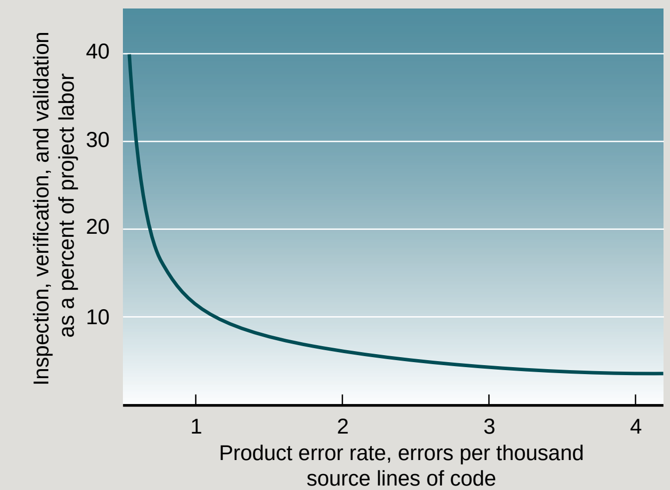

Figure 1. Data from IBM's Federal Systems Division indicate that when more effort is spent up front for inspection, verification, and validation, the product error rate decreases.

When Software Fails

Perhaps the best-documented example of the harm resulting from poorly designed software involved the Therac-25, an accelerator used in medical radiation therapy. The *IEEE Computer Applications in Power* reported, "Between June 1985 and January 1987, six known accidents involved massive overdoses by the Therac-25—with resultant deaths and serious injuries" at treatment centers around the U.S. and in Canada.[1] Between the patient and the Therac-25's radiation beam was a turntable that could position a window or an x-ray-mode target between the accelerator and patient, depending on which of two modes of operation was being used. If the window was positioned in the beam's path with the machine set to deliver radiation through the x-ray-mode target, disaster could result because software errors allowed the machine to operate in this configuration.

Engineering Reliable Software

Conditions such as these, where software was assigned sole responsibility for safety systems and where a single software error or software-engineering error could have catastrophic results, are precisely what Johnson's group aimed to avoid when it helped to prepare the portion of the NRC's recently published *Standard Review Plan*[2] regarding computer-based safety systems. Their process requires that software for nuclear power plant protection systems be written in accordance with good engineering practices. That is, software should follow a step-by-step approach of planning, defining requirements for worst-case scenarios, designing the software, and following a detailed inspection and testing program—

known as verification and validation—during each step of development and installation. This process avoids the pitfalls that can occur when software designers are expected to begin writing code before the design is complete, a process akin to pouring concrete footings for a building before knowing how tall the building will be.

Good engineering practices make for better software. But it is axiomatic in the safety-systems business that software can never be perfect. Figure 1, showing IBM's experience from the Space Shuttle program, illustrates the futility of attempting to produce perfect software for every need. The point of diminishing returns is reached well before perfection can be guaranteed.

When the consequences of failure are very high, safety-critical systems should always incorporate "defense-in-depth and diversity," which can be accomplished by incorporating different kinds of hardware, different design approaches, or different software programming languages. The idea is to have different kinds of systems available to accomplish the same goal; for example, a digital system is often backed up with a tried-and-true analog system. Then, if one system fails, a different system is in place to carry on. Simple redundancy, having two versions of the same system, is not enough because both could fail simultaneously as a result of the same flaw (Figure 2).

Many kinds of diversity are possible. Although only some scientific basis dictates what kinds of diversity are the best or how much diversity is enough, experience has shown an effective combination of protections to be the use of different hardware and software acting on different measurements to initiate different protective actions. Based on that experience, the NRC's *Standard Review Plan* requires that at least two independent systems, incorporating multiple types of diversity, protect against each worst-case scenario.

Making the Systems Better

The Institute of Electrical and Electronics Engineers has defined good engineering processes for the design of computer software, but there is little agreement on such specifics as notation, the preparation of specifications, or design and analysis methods. Testing is another challenge. As yet, although methodologies are available, there are no

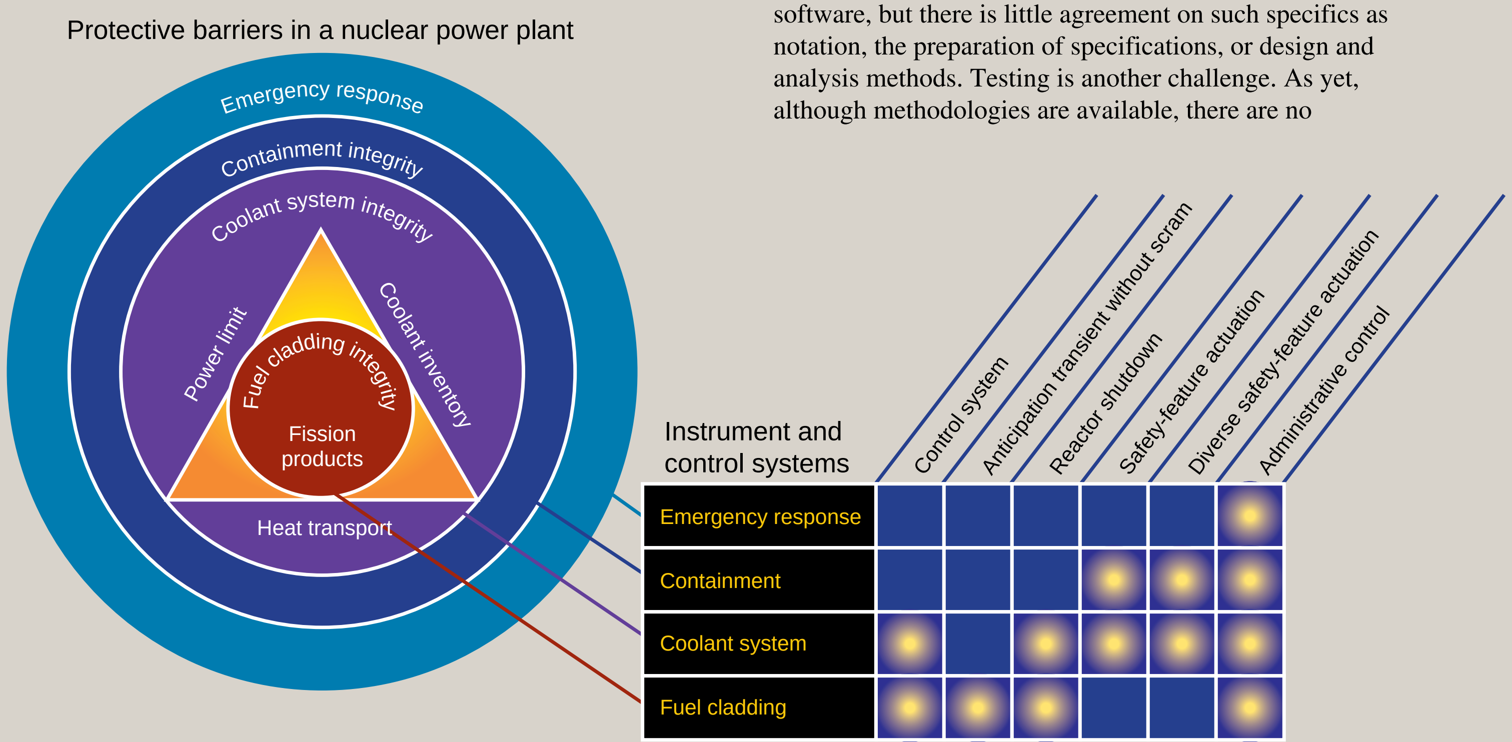

Figure 2. A diverse combination of software and hardware systems ensures that the overall safety of a nuclear power plant is not jeopardized by a single system failure. The large dots indicate various systems that protect the integrity of nuclear power plants.

mathematical equations or models that can be used to evaluate a software program to determine whether it is dependable or whether it contains errors and may fail.

Johnson's group has three projects under way that tackle the software quality issue head on—developing a method for determining the reliability of high-integrity safety systems, developing techniques to test commercial software, and developing methods for establishing the requirements to which software is written.

The first project is related to the current move toward "risk-based regulation," which uses assessments of risk to determine how to regulate. Livermore is developing a methodology for determining software reliability (and conversely, the failure probability of software). Information about software reliability will be integrated with hardware reliability measurements to form a measure of overall system reliability. The result will be used in NRC probabilistic risk assessment analyses.

In the second project, the group is looking for ways to "qualify" software that has not been through a rigorous development process, such as software that is frequently embedded in commercial instrumentation and control components. Demonstrating the dependability of such software is a challenge because thoroughly testing the large numbers of program states and combinations of input conditions is virtually impossible. The group is identifying techniques that limit the inputs and conditions that must be tested to qualify a software design. Considerable research has been done on software integrity, but this particular approach has not been tried before. If this project is successful, the process of introducing new control systems into nuclear power plants will be simplified.

The aim of the third project is to clarify the project goals, or requirements, that are developed before software programs for protection systems are written. Requirements must be carefully specified, but it is almost impossible to anticipate every situation. Livermore engineers are working with Sandia National Laboratories, Albuquerque, to adapt techniques used to design control systems for the defense industry. In the process, they are developing methods for determining the fundamental goals of a computerized control system.

As computers become more powerful and software more complex, projects such as these will go far to increase confidence in the reliability of systems designed to protect workers and the public.

– Katie Walter

Key Words: instrumentation and control systems, nuclear power plants, safety-critical systems, software engineering.

References

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2. U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, "Instrumentation and Controls," Chapter 7, *Standard Review Plan*, NUREG-0800, Rev. 4, June 1997.

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Keeping the "More" in Moore's Law

THE number of transistors that can be put on a computer chip tends to double about every two years, just as Intel Corp.'s co-founder Gordon Moore predicted more than 20 years ago. But lately, experts have been worried that Mr. Moore's law might falter as the laws of physics catch up with the ability to cram more and more on a chip. That's why Lawrence Livermore—with its skills in optics, precision machining, multilayer coatings, miniaturization, and a host of other capabilities developed in its weapons work—teamed up with fellow DOE laboratories Lawrence Berkeley and Sandia to literally shed new light on the subject. They also teamed up with three of the biggest names in the semiconductor industry—Intel, Motorola, and Advanced Micro Devices. The result is a $250-million project, funded by corporate money, to continue developing extreme ultraviolet (EUV) lithography technology.

The team's strategy has been to focus on specific technologies for EUV lithography, including multilayer coatings, projection optics, optical substrates, mask and optical design, and metrology (Figure 1). Livermore brings expertise in optics, precision engineering, and multilayer coatings; Sandia's part includes the systems engineering, the resists (protective coatings that prevent unwanted etching), and the light source. Berkeley provides its Advanced Light Source to characterize the optics and resists in the EUV range.

Traditionally, advances in optical lithography—a photography-like technique of using light to carve channels on silicon wafers—have relied on using shorter and shorter wavelengths of light, which can produce smaller features much as a razor can make a finer cut than a hacksaw. State-of-the-art techniques use ultraviolet (UV) light, and experts believe that chips will continue to follow Moore's law for another 10 years as even shorter wavelengths are used.

Current systems use UV light with a wavelength of 0.248 micrometer, to image a master pattern through lenses onto a silicon wafer that is covered by a resist. This technology can produce features of just 0.25 micrometer, or about one four-hundredth the width of a human hair.

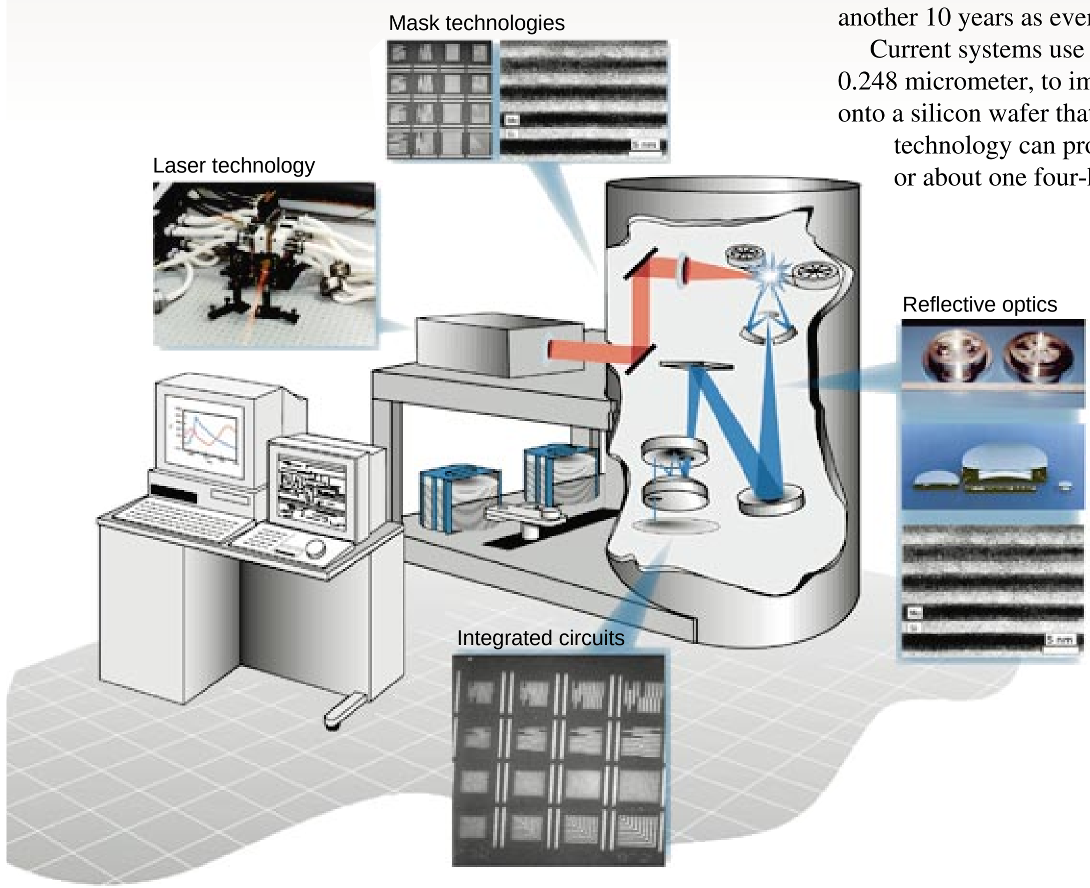

Figure 1. Spin-off and spin-back processes have boosted Livermore technologies for EUV lithography.

In less than 10 years, engineers plan to build chips with features measuring about 0.13 micrometer by using wavelengths of 0.193 micrometer. But beyond that point, physics intervenes and light shorter than that—called extreme ultraviolet light—will be absorbed, rather than refracted, by a conventional quartz lens. The result: no image.

Enter Multilayer Coatings

To solve the absorption problem associated with lenses, Livermore researchers turned to mirrors that reflect and focus the light on the chip. Called extreme ultraviolet lithography, the technique bounces EUV photons off an elaborate setup of mirrors, including a mask made of reflective materials, that ultimately focuses the photons on a resist-coated silicon wafer. By doing so, the Laboratory and its partners have designed an EUV system that can pattern features smaller than 0.05 micrometer.

But this method is not without its own technical challenges. The typical EUV mirror made with coatings of alternating films of silicon and molybdenum can reflect only about 65% of the photons that hit them. Because the photons in the EUV system are reflected nine times before they hit the wafer, the losses mount until only 1 to 2% of the original photons hit the target, which makes for long, costly exposure times. To make the system cost-effective, researchers must boost the reflectivity of the mirrors to at least 72%. However, Don Sweeney, the acting program leader for Advanced Microtechnology, says he thinks that goal can be reached in a few years. "Our researchers have already had some success in making higher-reflectivity mirrors from new combinations of materials."

Boosting EUV Lithography

Another important advance that assists the EUV lithography work is the development of the Ultra Clean Ion Beam Sputter Deposition System, the result of a collaboration between Lawrence Livermore and Veeco Instruments Inc. of Plainview, New York. That work earned an R&D 100 Award for the team in 1997 (see *S&TR*, October 1997, pp. 8–9).

The conventional method for making the reflective masks for EUV lithography is called magnetron sputtering. But the defect rate for the process is about 10,000 defects per square centimeter, far too many for successful EUV lithography. The new process, embodied in Veeco's IBSD-350, produces precise, uniform, highly reflective masks with 81 alternating layers of molybdenum and silicon, each 3 to 4 nanometers thick. As the machine directs a beam of ions at the masks, the ions physically collide with each mask and form a vapor, which is precisely deposited on it at a defect density of less than 0.1 per square centimeter—a 100,000-fold improvement over conventional methods. This process also holds great promise for a number of other applications using virtually any material or combination of materials including metals, semiconductors, and insulators. A near-term possibility is making very-low-defect-density films for ultrahigh-density heads for the magnetic recording industry.

Also boosting the EUV work is another R&D Award-winning Livermore invention—the Absolute Interferometer (see *S&TR*, October 1997, pp. 6–7)—which can measure large

The Incredible Shrinking Chip

Why are smaller computer chips better and faster? It might seem a paradox, but as the size decreases, the chips become more powerful. It's as simple as getting to grandma's house faster if she lives next door rather than across town: the electronic signals zipping around the circuitry to solve computing problems have less distance to travel. Today's chip contains about 3,260 times more transistors than the chip of 1971. Here's a chronology of the shrinking of chips as the semiconductor industry became a $150-billion enterprise.

Year	Microprocessor	Number of Transistors
1971	4004	2,300
1974	8080	6,000
1978	8086	29,000
1982	80286	134,000
1985	Intel 386	275,000
1989	Intel 486	1.2 million
1993	Pentium Processor	3.2 million
1995	Pentium Pro	5.5 million
1997	Pentium II	7.5 million

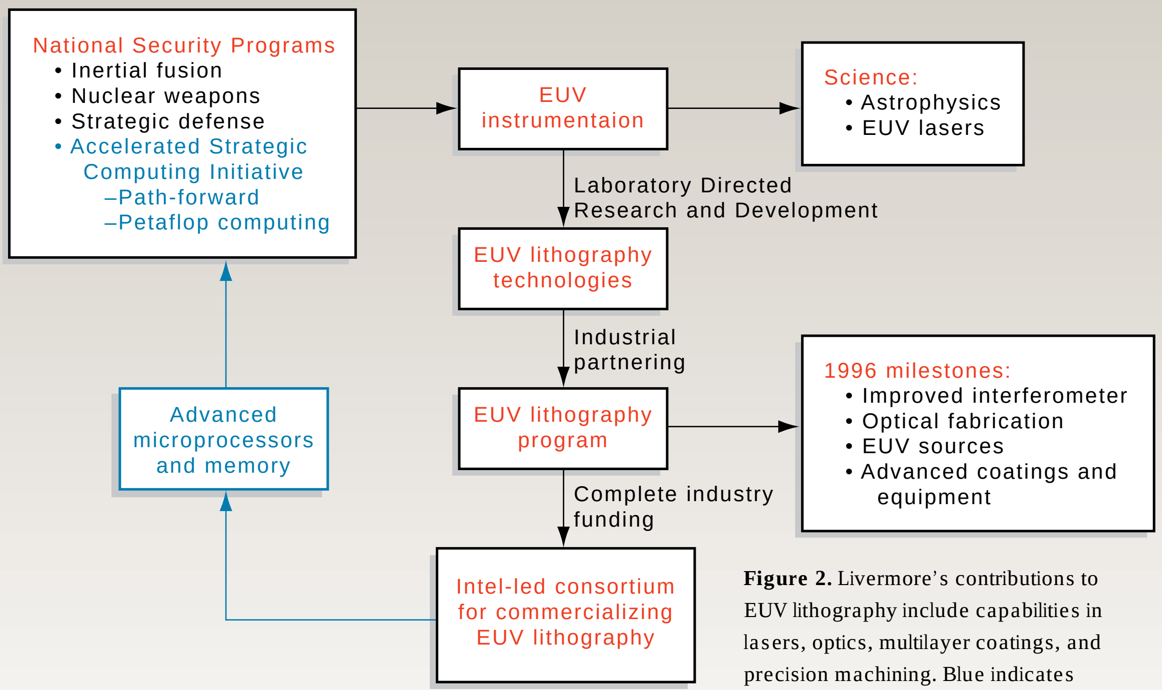

Figure 2. Livermore's contributions to EUV lithography include capabilities in lasers, optics, multilayer coatings, and precision machining. Blue indicates capabilities spun back to the national security programs.

surfaces to an accuracy of less than 1 nanometer, the thickness of a few atoms. This capability is essential to fabricate the nearly perfect mirrors necessary for EUV lithography because the processing requires surface-measurement feedback during the polishing process at a level of accuracy that conventional devices cannot provide.

But any of these technologies would not ensure the longevity of Moore's law by itself. "Intel came to us because we are the world leader in technology for EUV lithography," Sweeney says (Figure 2). "Our work grew out of our national security mission, and our multidisciplinary workforce allows us to integrate the technologies needed for this project. The commercialization of EUV lithography through the consortium is an exciting prospect for everyone who's interested in smaller and faster computing."

—Sam Hunter

Key Words: Absolute Interferometer, Advanced Microtechnology Program, extreme ultraviolet (EUV) lithography, Ultra Clean Ion Beam Sputter Deposition System.

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Patents and Awards

Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
William C. Moss	**Thermoacoustic Refrigerator** U.S. Patent 5,673,561 October 7, 1997	A thermoacoustic device having a thermal stack made from a piece of porous material, which provides a desirable ratio of thermoacoustic area to viscous area. The material has a low resistance to flow to minimize acoustic streaming, high specific heat conductivity, and low thermal conductivity. The inexpensive thermal stack can be formed of reticulated vitreous carbon and is easily formed in small sizes. A heat exchanger of heat-conductive, open-cell foam may be included. The thermoacoustic cooling device may be combined with a semiconductor device.
Anthony M. McCarthy	**Silicon on Insulator Achieved Using Electrochemical Etching** U.S. Patent 5,674,758 October 7, 1997	A manufacturing process for forming thin-film crystalline silicon circuits on arbitrary supports. The process includes four basic stages: preparation, bonding, thinning, and silicon region formation. The process takes silicon wafers with completed circuits, bonds the circuit side of the wafer to the support, and thins the wafer to remove excess silicon. Electrochemically enhanced etching is then used to define the circuits and expose the electrical contact regions. This process provides an economical thin-film silicon-on-insulator technique for microelectronics fabrication applications.
Kathleen I. Schaffers Laura D. DeLoach Stephen A. Payne Douglas A. Keszler	**Ytterbium-Doped Borate Fluoride Laser Crystals and Lasers** U.S. Patent 5,677,921 October 14, 1997	Ytterbium-doped borate fluoride host crystals, having a formula of $MM'(BO_3)F$, where M, M' are monovalent, divalent, and trivalent metal cations. The crystals can be used in laser oscillation and amplifiers. A particular composition is Yb-doped $BaCaBO_3F$ (Yb:BCBF). Because BCBF and some related derivative crystals are capable of nonlinear frequency conversion, whereby the fundamental of the laser is converted to a longer or shorter wavelength, these new crystals can simultaneously serve as self-frequency doubling crystals and laser materials within a laser resonator.
Roger D. Aines Robin L. Newmark	**Active Cooling-Based Surface Confinement System for Thermal Soil Treatment** U.S. Patent 5,681,130 October 28, 1997	A process for the use of a thermal barrier to control the ground subsurface pressure by active cooling. This barrier is placed in contact with the ground surface, and a region underneath the barrier is heated for remediation. The cooling capacity of the barrier is controlled so that rising gases and vapors in the soil are condensed and confined beneath the barrier. The subsurface pressure is thereby controlled by controlling the surface temperature. This method is useful for thermal remediation involving steam injection. The thermal barrier prevents steam breakthrough during thermal remediation of shallow underground contaminants.
Thomas E. McEwan	**Pulse Homodyne Field Disturbance Sensor** U.S. Patent 5,682,164 October 28, 1997	An inexpensive field-disturbance sensor that transmits a sequence of transmitted bursts of electromagnetic energy. The transmitter frequency is modulated at an intermediate frequency. The sequence of bursts has a burst repetition rate, and each burst has a burst width and comprises a number of cycles at a transmitter frequency. The sensor includes a receiver that receives electromagnetic energy at the transmitter frequency and a mixer that mixes a transmitted burst with reflections of the same transmitted burst to produce an intermediate-frequency signal. A second range-defining mode transmits two radiofrequency bursts, where the time spacing between the bursts defines the maximum range divided by two.

Awards

Richard W. (Dick) Lee and **Max Tabak** have been elected **Fellows of the American Physical Society** for their outstanding contributions to physics. Among the 179 fellows elected in 1997, they are both members of the society's Plasma Physics Division. Lee, a senior scientist in the Physics and Space Technology Directorate office, was recognized "for technical contributions and outstanding outreach of codes for plasma spectroscopy." A physicist and group leader for inertial confinement fusion in the Defense and Nuclear Technolgoies Directorate, Tabak was cited for "his exceptional inventive and broad contributions to the fields of laser and particle-driven inertial fusion, and in particular for being the principal inventor of the fast ignition concept."

IndustryWeek magazine selected **Charles Alcock** as one of the nation's top 50 R&D "stars" for his research on dark matter, known as MACHOS (Massive Compact Halo Objects).

Kennedy Reed, named the winner of the **International Center for Theoretical Physics Visiting Scholar Award**, traveled to the University of Dakar in Senegal and the University of Cape Coast in Ghana to fulfill duties of the award, which included consulting and leading seminars.