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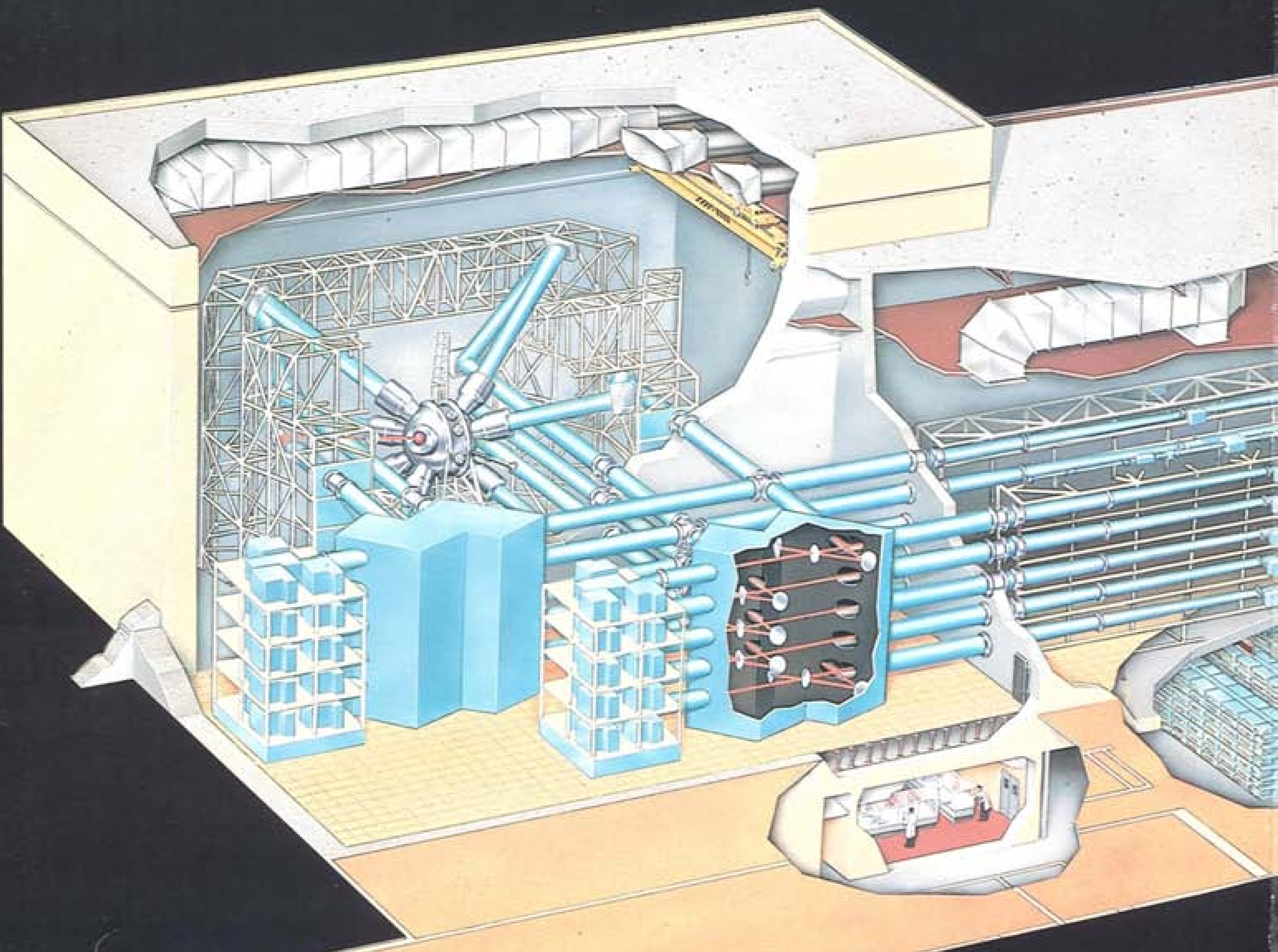
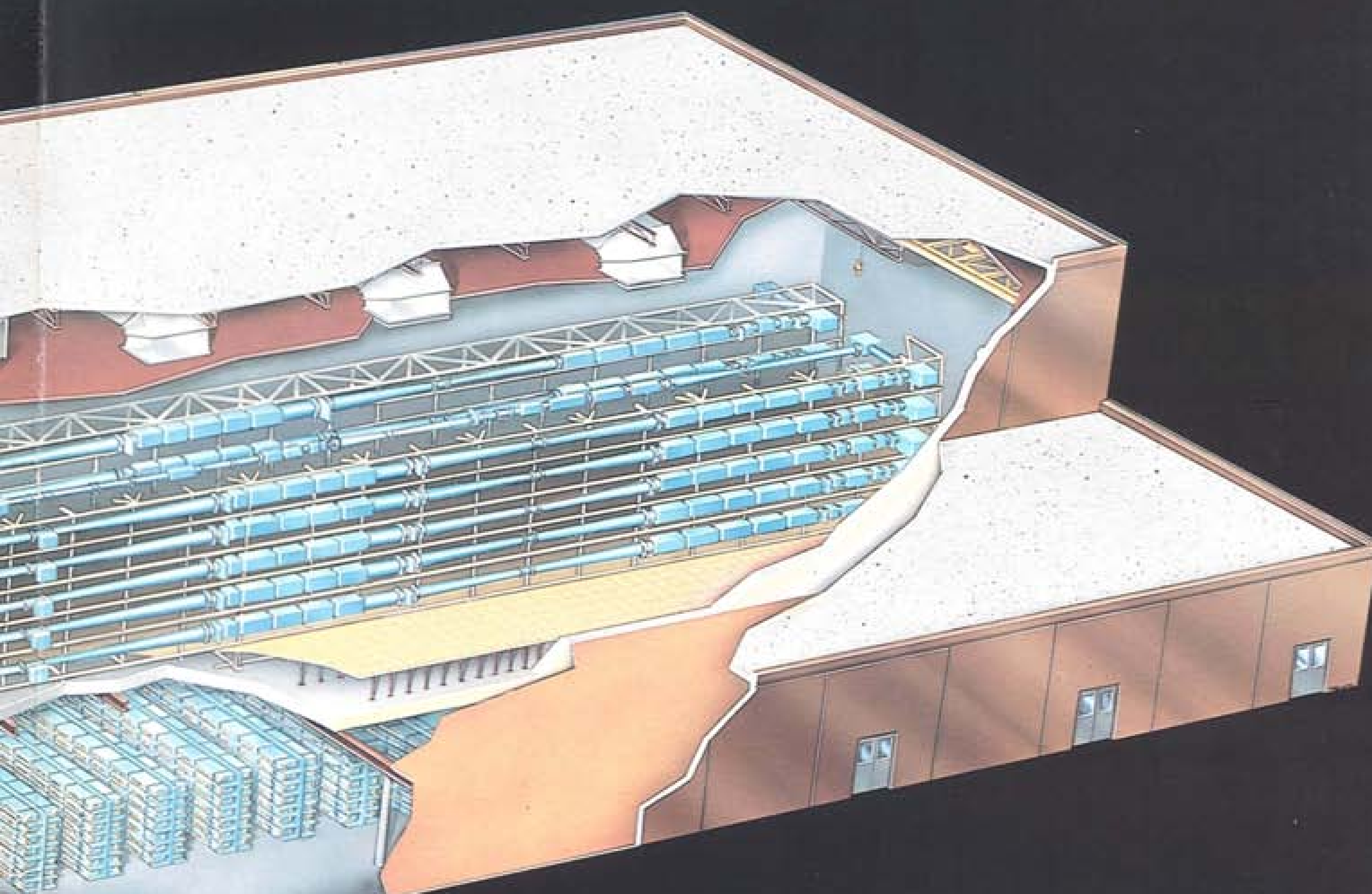
Energy and Technology Review

Lawrence Livermore National Laboratory

February 1985



Nova Dedication Issue



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About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. Since then, we have added other major programs, including laser fusion and laser isotope separation, biomedical and environmental sciences, and applied energy technology. These programs, in turn, require research in basic scientific disciplines, including chemistry and materials science, computer science and technology, engineering, and physics. The Laboratory also carries out a variety of projects for other Federal agencies. *Energy and Technology Review* is published monthly to report on unclassified work in all our programs. A companion journal, *Research Monthly*, reports on weapons research and other classified programs. Titles from recent issues of *Energy and Technology Review* are listed opposite the inside back cover.

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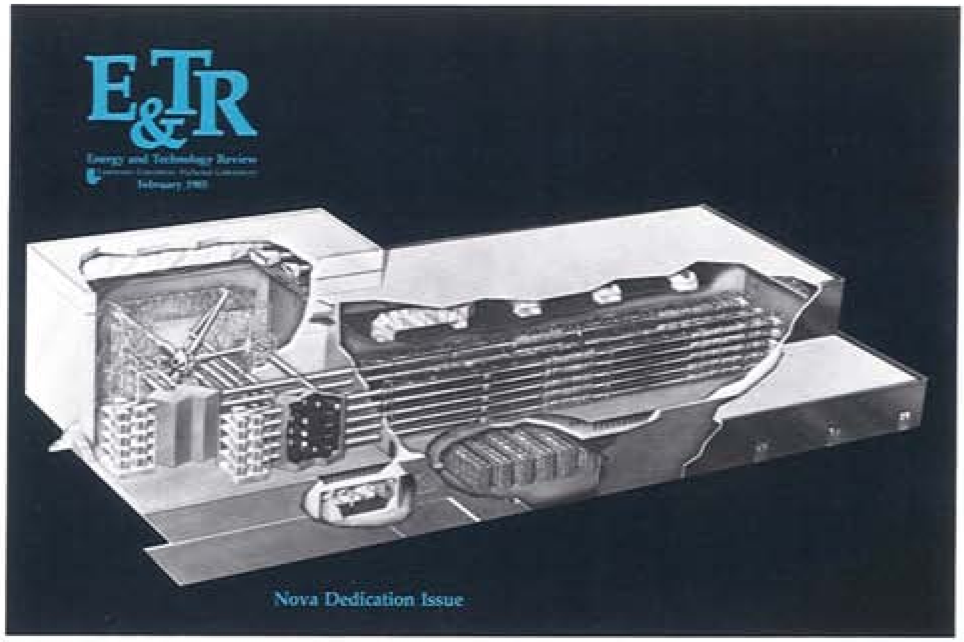

About the Cover

Detailed artist's rendering of the Nova laser system, the latest in LLNL's evolutionary series of large research lasers. It has two principal missions: to study the physics of nuclear weapon design and to develop the technology of inertial confinement fusion for eventual application to commercial power generation. The ten-beam, neodymium-glass laser operates at three wavelengths (infrared, green, and blue) and delivers from 120 to 70 kJ of energy, depending on the wavelength used. Each of Nova's ten amplifier chains is 137 m long; the fundamental infrared wavelength is converted to green or blue light by passage through arrays of potassium dihydrogen phosphate crystals just before each beam enters the massive target chamber. This issue of *Energy and Technology Review* is devoted to the Nova laser project—the various technologies developed, our relations with industry and technology transfer, and the management of the entire project.

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Neodymium-Glass Laser Research and Development at LLNL

During the past decade, we have designed and constructed a series of increasingly energetic and powerful neodymium-glass solid-state lasers for research in weapon physics and in inertial confinement fusion (ICF). The twofold focus of our continuing efforts in laser research and development is on (1) the design and fabrication methods that will significantly reduce the cost of a 10-MJ, 500-TW laser system, and (2) the development of techniques for operating solid-state lasers at high average power and efficiency.

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For more than a decade, LLNL has been centrally involved in the nation's inertial-confinement fusion (ICF) program. The principal goals of the ICF program are to produce, in the laboratory, high-gain implosions of the fusion fuel, to apply ICF technology and facilities to nuclear-weapon physics research and to military applications, and, ultimately, to generate cost-effective, central-station electric power. In direct support of this program, we have developed the technology base and increased the energy and peak power levels of neodymium-glass lasers by several orders of magnitude. On the occasion of the initial operation of the most recent of these laser systems, Nova, it is appropriate to review the strategic technical issues of inertial fusion that we addressed in the early 1970s, to outline the considerations that led to the selection and subsequent development of neodymium-glass systems for ICF and weapon-physics research, and to highlight some of the key accomplishments of the development campaign.

Origin of the ICF Program

In inertial confinement fusion, high-power laser beams rapidly heat the surface of a target capsule, usually containing a deuterium-tritium fuel mixture, to form a plasma envelope. The rocket-like blowoff of plasma material from the surface drives the capsule inward to compress and heat the fuel. When the core reaches a density of 10^3 to 10^4 times that of liquid water and a temperature of 10^8 degrees (10 keV), the fuel ignites. Thermonuclear burn spreads rapidly throughout the compressed and inertially confined fuel, yielding many times the driver input energy. Shortly after the invention of the ruby laser in 1960, computer calculations were made at LLNL to simulate the irradiation of tiny deuterium-tritium (D-T) pellets by intense pulses of laser light and their subsequent implosion to thermonuclear conditions. At this same time, it was recognized that the fusion microexplosions could eventually be applied to the generation of power. Calculations revealed, however, that efficient generation of fusion energy would not result from simple laser heating of the thermonuclear fuel. Instead, to generate fusion energy, lasers would have to compress and implode the fuel to 10 000 times its liquid density.

Experimental work to create hot plasmas using lasers began in the mid-1960s at several laboratories including LLNL. Neutron generation from planar lithium-deuteride targets was reported by Soviet researchers in 1968. With this demonstration of neutron generation from laser-heated plasmas, interest intensified in seeking an answer to the basic question: Can we design fusion pellets that will produce useful thermonuclear gain (that is, release during thermonuclear fusion more than 100 times the energy used to implode the fusion fuel) when driven by technologically and economically practical lasers?

The best available computer-based estimates for laser-driver requirements with gains of 100 were many orders of magnitude beyond the energy and peak power levels of lasers available in the early 1970s. Thus, it became evident that the minimum drive requirements could (and should) be determined using experimentally flexible, single-shot laser systems, and that development of the efficient, repetitively pulsed laser systems needed for the more demanding fusion applications could (and should) be undertaken separately and at a rate consistent with growing knowledge of the minimum drive requirements.

Selection of Lasers for ICF

In 1971 and 1972, the U.S. Atomic Energy Commission and its nuclear weapons laboratories at Livermore and Los Alamos recommended to Congress that dedicated irradiation facilities capable of producing more than 10 TW of peak power should be undertaken as the next step in the U.S. inertial fusion effort. At that time, both laboratories were engaged in exploratory development of several types of lasers for possible use in inertial confinement fusion, including carbon dioxide, neodymium-glass, hydrogen fluoride, and atomic iodine lasers. Because it was judged that all of these lasers could, with sufficient development, be scaled to the required energy and peak power levels, selection of which types to pursue was centered on the operating wavelengths of the lasers and on their potential for high average power and efficiency.

Analyses of plasma physics, coupled with LLNL computer calculations, indicated that it would be highly beneficial to deliver the bulk of the energy to the target at shorter wavelengths[1]; at a short enough wavelength, the laser radiation incident on the fusion pellet would be absorbed primarily through inverse bremsstrahlung, and a thermal plasma would be created. These computations also enabled us to identify and characterize a number of undesirable competing energy-absorption processes that, at longer wavelengths, would lead to nonthermal plasmas and to deleterious preheating of the fusion fuel. Analyses of the activation thresholds for these detrimental absorption mechanisms indicated that their thresholds would be higher when shorter-wavelength laser light was used.

Although we could not, at that time, project quantitatively the laser intensity at which these unwanted processes would occur, it was clear that by selecting a laser driver with the shortest operating wavelength, the physics risk in driving efficient dense implosions would be significantly reduced. Thus, on the basis of wavelength considerations alone, the neodymium-glass laser became the laser of choice because it has the shortest operating wavelength of 1.05 μm (compared to 10.6 μm for carbon dioxide, 2.70 μm for hydrogen fluoride, and 1.315 μm for atomic iodine). Anticipating that even a 1.05-μm wavelength might not be short enough, we noted that small-scale laboratory experiments had demonstrated the scientific feasibility of using nonlinear harmonic-converter crystals to efficiently shift the 1.05-μm output radiation of a neodymium-glass laser to green (0.525-μm), blue (0.350-μm), and ultraviolet (0.265-μm) light.

In addition to these desirable characteristics, the neodymium-glass laser offers the flexibility in pulse width and pulse shape required for a research-oriented irradiation system designed to explore a wide variety of target designs and physics phenomena. The efficiency and average power potential of the neodymium-glass laser, however, was judged to be inadequate for the projected laser-system requirements for civilian applications (e.g., power generation). Of the types of laser considered, the carbon dioxide laser looked to be the other most promising laser, offering the potential for high efficiency and average power but operating at a relatively long wavelength. Because, in the early 1970s, it was uncertain just how short the irradiation wavelength had to be to achieve a high-gain implosion at a practical laser energy and power level, and because the development of ICF technology would necessarily take several decades, a decision was made to explore more than one research and development strategy.

Within the U.S. ICF program, the Los Alamos National Laboratory elected to pursue the long-wavelength approach to ICF, with the objective of exploiting the efficiency and average power potential of the carbon dioxide laser. Los Alamos has since successfully developed carbon dioxide laser technology to the 40-kJ, 50-TW level with their Antares laser system brought on line in 1984.

We at LLNL decided to pursue the short-wavelength approach to ICF with a two-pronged laser research and development strategy. Neodymium-glass laser systems (fitted with harmonic converters, if necessary) would be developed in a sequence of experimentally flexible, single-shot, fusion-target irradiation facilities. Concurrently, we would search for and develop new, short-wavelength lasers with the efficiency, average power, and cost potential required for high-average-power ICF applications (e.g., production of special nuclear materials for military applications, breeding fuel for light-water reactors, and producing electric power for civilian applications).

Developing the Neodymium-Glass Laser

In 1972, the principal elements of the neodymium-glass technology base were limited to (1) a series of neodymium-glass rod amplifiers and systems designed by Compagnie Generale d'Electricité in France, (2) face-pumped disk amplifiers of approximately 10-cm aperture developed at LLNL and at the Naval Research Laboratory, and (3) a relatively high-performance lithium silicate laser glass (ED-2) developed and manufactured by Owens-Illinois of Toledo, Ohio. Laser systems of the day were able to generate peak power outputs of approximately 300 GW in a 1-ns pulse.

From this starting point, we launched a broadly based, long-term effort into the research and development of neodymium-glass lasers. In the 13 years since then, we have designed and constructed a sequence of neodymium-glass laser systems at LLNL, culminating in our largest and most powerful system ever, the 100-TW Nova laser. Figure 1 summarizes the energy, peak-power, and pulse-width capabilities of the Janus, Cyclops, Argus, Shiva, and Nova laser systems. The Nova laser will be capable

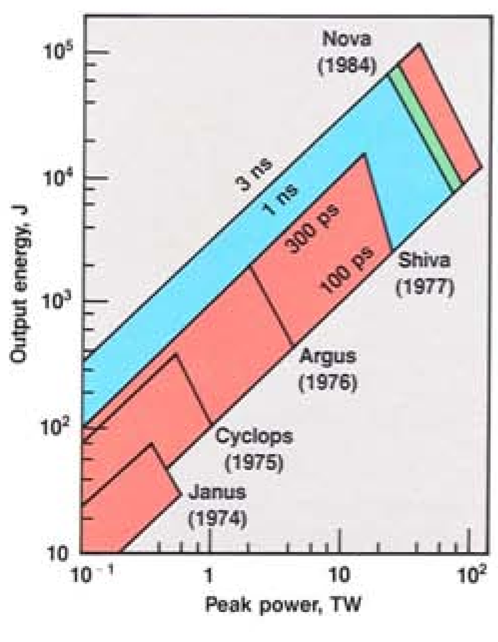

Fig. 1

Energy, peak-power, and pulse-width capabilities of the neodymium-glass laser systems constructed and operated at LLNL during the past decade. The Nova laser system can operate at 1.05, 0.525, and 0.35 μm; the others operate only at 1.05 μm.

of generating output radiation at 0.525 and 0.350 μm, as well as at its fundamental 1.05-μm wavelength.

The Shiva laser (10 to 25 TW) was a $25-million line item authorized by Congress in 1973 and operated in 1977. It was the technological fulcrum of our entire laser-development enterprise. The results of the research and engineering efforts undertaken to create the Shiva laser were so successful that it became possible to construct neodymium-glass laser systems with peak power and energy levels orders of magnitude greater than Shiva's. These advances also made possible significant reductions in the unit cost of laser output energy in each succeeding, larger laser system. The technical issues and research results leading to the realization of such dramatically improved system performance levels have been discussed in the technical literature.[2]

Performance Limitations

There are two phenomena that still limit the performance of neodymium-glass lasers. The first is the small-scale self-focusing of the laser beam, which arises from the intensity-dependence of the nonlinear refractive index (n_2) of optical materials. The second phenomenon is the catastrophic damage that occurs at high beam fluences to the optical components located in the beam path. We initiated research efforts to find laser glasses and other optical materials with lower nonlinear refractive indices (n_2), to develop beam control and propagation techniques to minimize beam degradation in the presence of a nonvanishing n_2, and to develop optical materials with significantly higher damage threshold fluences.

New Optical Materials

Following the development of a theoretical model relating n_2 to the material's linear refractive index (n) and to its dispersion (expressed by the Abbe number, ν_d), rapid progress was made in developing optical materials with lower n_2 values. Experimental n_2 data on a wide variety of glasses confirmed the quantitative predictive value of this model. As shown in Fig. 2, curves of constant n_2 can be overlaid on the linear-index/dispersion plane. Optical glass companies routinely report the linear index and dispersion of the many thousands of glass compositions they formulate, enabling us to obtain readily the n_2 values for these glasses. Thus, we were able to target for development a number of glass compositions characterized by n_2 values lower than those of the silicate glasses (e.g., phosphates, fluorophosphates, and fluoroberyllates).

We also developed a theory of neodymium-ion transition probabilities to relate the laser properties of a glass to its composition. This model, together with the linear-index/dispersion model, provided us with a powerful predictive tool for identifying new neodymium-glass compositions with substantially superior laser performance capabilities. Glass manufacturing companies (Owens-Illinois, Hoya Corporation, Schott Optical Company, Kigre, and Corning) participated throughout this effort, providing expertise on glass-forming science and production.

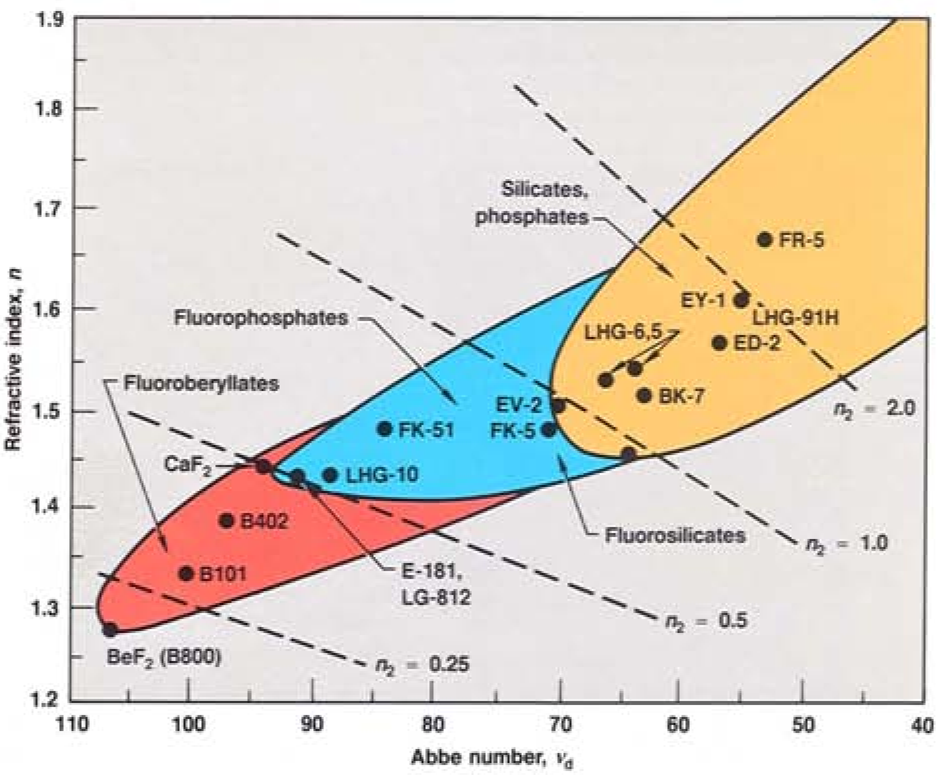

Fig. 2

Location of various silicate, phosphate, fluorophosphate, and fluoroberyllate laser glasses in the refractive-index/Abbe-number plane. (Abbe number is the reciprocal of the material's index of dispersion.) The locations of several fluoride crystals also are shown. Curves of constant nonlinear refractive index (n_2) are indicated by the dashed lines.

Beam Control

A major advance in laser beam control was achieved in 1976 with the introduction of the relay-imaging spatial filter. Essentially a telescope with a diamond pinhole at the common focus of the lens pair, this device performs two separate functions when it is placed in a chain of laser amplifiers. First, it expands the diameter of the laser beam as it passes from smaller diameter amplifiers to larger ones, maintaining the beam fluence along the chain below the fluence thresholds for optical damage. Second, it removes small-scale intensity and phase noises in the laser beam as the beam passes through the pinhole, preventing the build-up of deleterious hot spots in the beam. With this spatial-filtering technique, the peak-power output of the Argus laser system was increased from 2 TW to more than 4 TW using simple relay-imaging optics. The principle of relay-imaging spatial filtering is now incorporated, worldwide, in the design of all high-power neodymium-glass laser systems.

Optical Damage

The key to our success in reducing damage to optical materials was the decision to build high-quality laser-irradiation facilities and beam diagnostics with which to make accurate and repeatable damage-threshold measurements. We worked closely with optical fabrication companies (Eastman Kodak, Zygo Corporation, Tinsley Laboratories, and Perkin-Elmer Corporation) and optical coating companies (Optical Coating Laboratory, Inc., Spectra-Physics) to prepare large numbers of substrate and coated elements (antireflection, high-reflection, polarizing) under varied but reproducible conditions. Damage-threshold measurements made at LLNL were used to identify the most promising optical-element designs, materials, and production methods. Because this research and development process was conducted directly with the optical component manufacturers, the results could be translated into production optics with minimal delay and cost. A measure of the success of these efforts is illustrated in Fig. 3, which shows the fivefold increase in the damage threshold fluence of antireflecting surfaces achieved in collaborative research efforts with Corning, Owens-Illinois, Schott Optical Company, Hoya Corporation, and Westinghouse. Because antireflecting surfaces typically are the most heavily stressed optical surfaces in laser systems, the development of these high-damage-threshold optical components has had a profound impact on high-performance lasers.

Shorter Wavelengths for Nova

The sequence of LLNL laser systems (see Fig. 1) has been used, over the years, to conduct a large number of laser–plasma interaction and implosion experiments. Experiments with the Argus and Shiva lasers showed that 1.06-μm light produced a nonnegligible number of the hot electrons that cause deleterious preheating of the fusion fuel. These and similar observations made at other fusion-research laboratories prompted fusion researchers to undertake similar measurements at shorter wavelengths, converting the 1.05-μm fundamental wavelength of existing neodymium-glass lasers to shorter wavelengths. Experiments using green, blue, and ultraviolet light showed a strong decrease in the hot-electron

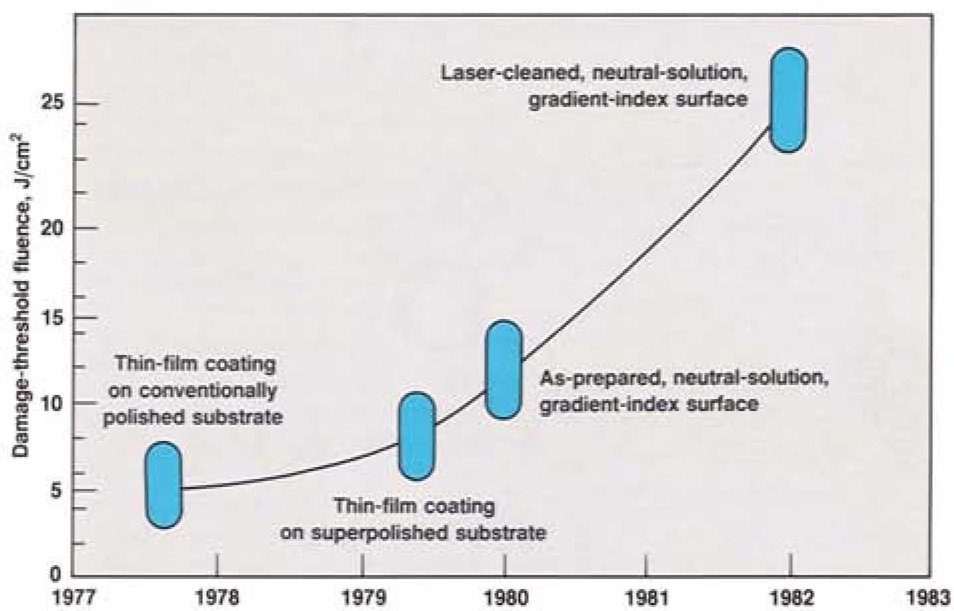

Fig. 3

A fivefold improvement in the damage-threshold fluence of antireflecting surfaces has been achieved at LLNL in the past few years (incident laser wavelength of 1.06 μm, pulse length of 1 ns). Because antireflecting surfaces are the most severely stressed optical surfaces in high-performance laser systems, development of such coatings with high damage thresholds has made a significant impact on the performance capabilities of laser systems.

fraction as the wavelength was shortened, particularly between 1.05 and 0.525 μm. The fraction of incident laser light absorbed and the ablation pressure produced also increased significantly at shorter wavelengths. On the basis of these highly favorable results, we revised the Nova performance specifications from the original 250 kJ of 1.05-μm light to the more target-effective specification of 100 kJ of 1.05-μm light with conversion to green and blue light.

Beyond Nova

Our research and development efforts have been so successful that we are now assured that short-wavelength laser systems can, indeed, be scaled to 10 MJ and 500 TW. These energy and power levels should be sufficient to drive the high-gain fusion targets required for the more demanding single-shot weapon-physics research and military applications.

If, however, such a laser system were to be constructed with Nova technology and the current master-oscillator/power-amplifier (MOPA) system architecture, the cost would be prohibitive. Consequently, for the past year or so, we have been engaged in an effort to design and assess new cost-effective system architectures, to develop new higher-performance laser materials, and to develop large-capacity, low-cost components. Although it is still too early to be certain that 10-MJ-class lasers can be constructed for the budgetary goal of \$25 to \$50 per joule, large reductions in some of the major cost items appear possible, and we are continuing our efforts to obtain similar reductions for those items that are still driving up the system cost.

Other Short-Wavelength Lasers

The second prong of our laser research and development strategy has focused on those short-wavelength lasers that have an efficiency, average power, and cost suitable for the proposed ICF applications requiring repetitively pulsed operation (e.g., power generation, fuel production). These research efforts initially were centered on gas laser media because high average power could be realized by convectively removing the waste heat. In addition, in the early 1970s, only very poor efficiency and average power performance had been demonstrated for neodymium-glass and other solid-state lasers.

Between 1974 and 1979, a variety of energy-storage and steady-state gas lasers were proposed, developed, and assessed for use in fusion applications. The KrF excimer laser, fitted with one of several forms of pulse compression, proved to be the best of the systems investigated. After further study, however, the KrF laser in its present form was judged to be marginal in efficiency (below 6%), extremely complex optically because of the need for pulse-width compression, and several times too expensive for the end-use applications of ICF. We are continuing to seek a breakout from these limitations on KrF and other excimer laser systems.

At the same time we are reexamining the potential of solid-state lasers to operate efficiently in a repetitively pulsed mode. Our analyses[3] are based on new solid-state laser design concepts and new pumping sources, host materials, and laser ions. With these advances, unconstrained scaling of average power while maintaining high beam quality does appear possible if we use an amplifier geometry consisting of thin slabs of gain medium that are flow-cooled on their two large surfaces. Furthermore, with careful conservation of pump photons by a variety of well-identified techniques, efficiencies in excess of 10% should be possible at high power and radiance. We are now engaged in an effort to validate these ideas and to thoroughly assess the new materials and pump sources.

ICF Program Philosophy

The fast-paced (10-year) development and deployment of highly functional neodymium-glass target irradiation systems exceeding 100 TW is a singular accomplishment by any measure. Several key institutional, programmatic, and managerial factors have allowed this to occur. First, our laser research and development has been conducted in the context of a "full spectrum" program. That is, the users of the laser technology and systems being developed are actively involved—organizationally, programmatically, geographically, and psychologically—in the development process itself. This has minimized feelings of underachievement by the laser developer and overexpectation by the user. It has also ensured that both parties share a common commitment to the success of the program as a whole.

Second, long-term laser development goals were clearly established at the outset. Very early on, we examined the physical phenomena involved in inertial fusion, identified those of highest leverage, and identified, to the best of our knowledge, their parametric dependences on laser-radiation parameters. Requirements for end-use laser systems also were estimated (e.g., reactor drivers). Because of our limited knowledge, these analyses were quite judgmental. They did, however, provide us with a very valuable framework against which to compare the potentials of the laser media then known, to select primary and back-up approaches, to engage in a comprehensive research and development effort, and to establish programmatically rational intermediate and ultimate goals.

Third, our most realistic estimates of technical risk, cost, and schedule to accomplish various laser milestones were presented directly to our sponsors (initially the Atomic Energy Commission, then the Energy Research and Development Administration, and now the Department of Energy). Commitments were made to specific milestones on the basis of available and adequate funding. Resources were expended as needed throughout the research and development efforts without placing artificial constraints on the actual dollar amounts allocated to research versus to development (as is often done in the Department of Defense). It was thus possible to capitalize rapidly on research advances while the laser-system facilities were being developed and constructed.

Lastly, especially at LLNL, heavy use has been made of computer modeling, off-line facilities for development and testing, and extensive diagnostics. Significant commitments to the development of new materials also were made. We have realized a manyfold return on these investments in terms of laser-system performance, schedule, and cost. These policies, prerogatives, and practices operating within the DOE-LLNL system represent an enormous strength as we continue to pursue the goals of the national ICF program.

Conclusion

As a result of our 13 years of intensive research and development, our innovative approach to program management, and our effective working relations with industry, we have established the premier ICF fusion research facility (Nova) in the world today. Additionally, we have defined a technological pathway extending from single-shot, neodymium-glass, fusion-research lasers to efficient, high-average-power, solid-state drivers for future ICF fuel- and power-producing applications.

Key Words: inertial confinement fusion (ICF)—research and development; laser—Argus, Cyclops, KrF, Janus, neodymium-glass, Nova, Shiva, short-wavelength, solid-state.

Notes and References

1. J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, *Nature*, **239**, 139–142 (1972).
2. J. F. Holzrichter, *et al.*, Lawrence Livermore National Laboratory, Rept. UCRL-52868 (1982).
3. J. L. Emmett, W. F. Krupke, and W. R. Sooy, *The Potential of High-Average-Power Solid State Lasers*, Lawrence Livermore National Laboratory, Rept. UCRL-53571 (1984).