Managing the Nova Laser Project

The Laboratory's Nova laser, the most powerful in the world, is now operational. Effective management minimized the impact on costs and schedules of fluctuating levels of construction funding and coordinated the contributions of many subcontractors, both large and small.

For further information contact Robert O. Godwin (415) 422-5548.

Experiments with the Laboratory's Nova High-Energy Laser Facility will begin in February 1985. The Nova laser is the latest in LLNL's evolutionary series of large neodymium-glass research lasers.

The Nova facility consists of two conventional structures, a 5500-m^2 office building and a 10 700-m^2 laboratory building, plus the large laser system. The ten-beam, neodymium-glass laser operates at three wavelengths, delivering in a 3-ns pulse 80 to 120 kJ at 1.05 μm (infrared), 50 to 80 kJ at 0.525 μm (green), or 40 to 70 kJ at 0.35 μm (blue). Each of Nova's ten amplifier chains is 137 m long; the fundamental wavelength (1.05 μm) is harmonically converted to green or blue wavelengths by unique arrays of potassium dihydrogen phosphate KDP crystals just before each beam enters the massive target chamber (Fig. 1). Nova's electrical system includes 10 000 capacitors, 5000 flashlamps, and 110 000 m of high-voltage electrical cable. Its optical systems comprise 1000 major components, incorporating:

- 2000 litres of laser glass.
- 1000 litres of fused silica.
- 10 000 litres of crown glass.
- 150 litres of crystals.
- 200 m^2 of optical-quality surfaces.
- 100 m^2 of optical thin-film coating.

(For details of Nova technology, see the article beginning on p. 8 of this issue.)

History of the Nova Laser

Over the past several years, LLNL has built and operated a series of increasingly powerful and energetic laser systems. (See the article on p. 1 for a perspective on neodymium-glass laser research and development at LLNL.) Each of these laser systems was more powerful than its predecessor by a factor of five to ten. Shiva, for example, was a 10-kJ laser, and Nova is a 100-kJ system. In constant dollars, the cost of each laser system scales roughly as the square root of its performance.

The idea of the Nova laser was born in 1975, about midway through the construction of its immediate predecessor, the Shiva laser. Nova was, in fact, originally conceived as an upgrade of Shiva; in some of the early documentation, it is referred to as Shiva* ("Shiva Star"). During the conceptual study for Nova, however, we decided that the most effective way of exploiting

what we had learned from Shiva would be to scale up the technology by an order of magnitude. The result clearly would be more impressive than a star; hence, "Nova." (For a while, it was known as Shiva-Nova.)

Funding of the Nova project was preceded by two years of conceptual planning and development funding. In fiscal year 1978, Congress authorized the project at $195 million; it will be completed at $176 million. Because of its size, the Nova laser facility is a congressionally funded line item—that is, a specifically identified construction item in the Federal budget. Although the project was authorized by Congress at the outset, funds had to be appropriated annually. This led to differences between funds requested by LLNL and actual funding levels. As a result of the variable funding levels and some modifications of the project's technical scope, it has gone through a number of cost and schedule changes. (For example, Nova's original design called for twenty beams operating at a single frequency in the near-infrared.) Figure 2 shows the history of the Nova project schedule and milestones.

When the Shiva laser was dismantled in 1981, the Laboratory faced a hiatus in large-laser experiments until Nova would become operational in 1984 or 1985. To bridge the gap, and to provide a test bed for Nova components, we decided to assemble an interim laser system. This facility, named Novette, was built in just 13 months and incorporated the first two Nova amplifier chains. This proved to be a prudent decision. In addition to enabling early verification of Nova hardware, Novette's experiments have exceeded our expectations from a physics standpoint. Among its achievements were a demonstration of wavelength scaling of fusion reactions and, of at least equal importance, the first confirmed demonstration of lasing at soft-x-ray wavelengths in a laboratory facility. Novette was operated for 18 months before it was dismantled last year for

Fig. 1

Target chamber of the Nova laser. Nova's ten beams converge to heat and compress a tiny deuterium-tritium-filled fuel capsule.

incorporation into Nova, having served its purpose most admirably.

Nova Project Management

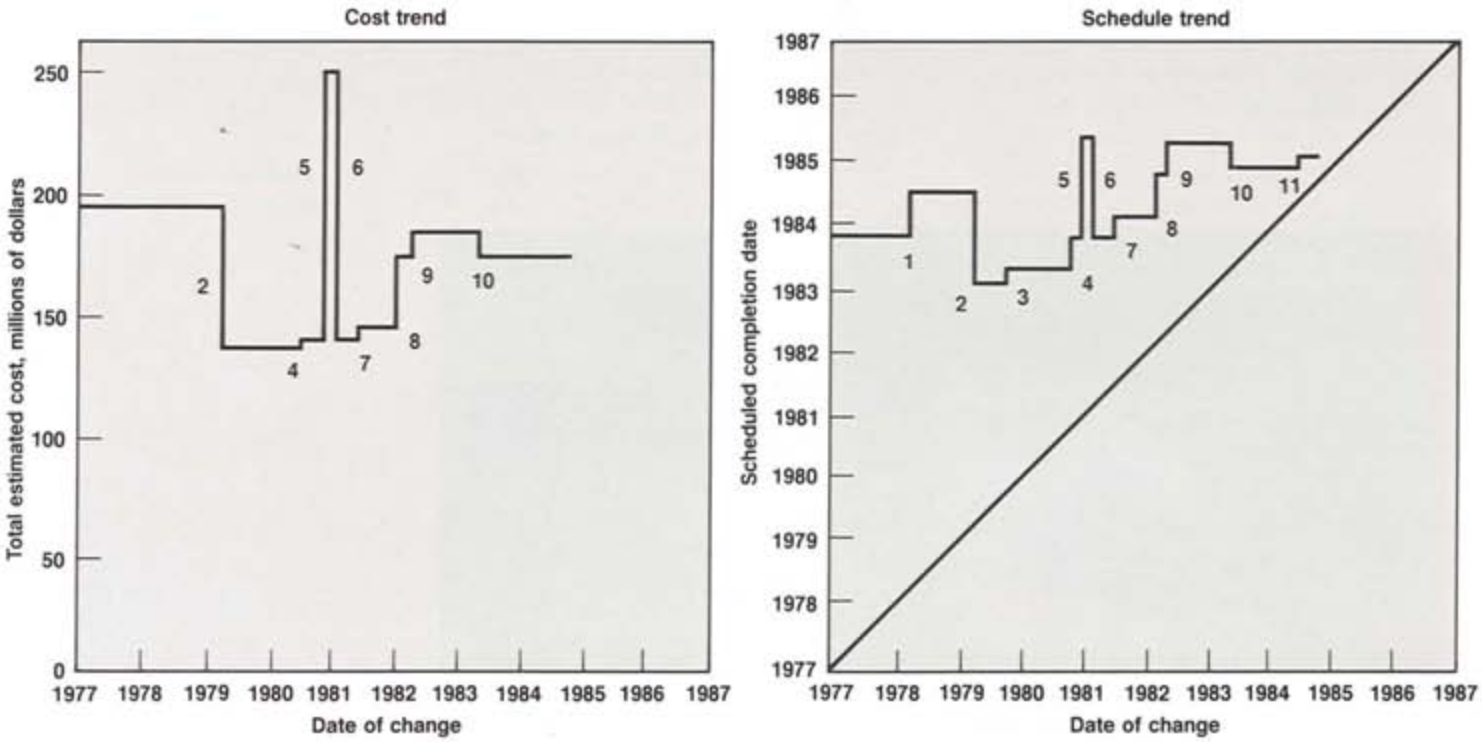
Under Department of Energy (DOE) guidelines, a project budgeted for more than about $50 million is classified as a major system or a major system acquisition. This brings it under DOE regulations, which spell out specific project management techniques, milestone requirements, and reporting procedures. (The only other Laboratory project subject to such controls is the Magnetic Fusion Test Facility-B, scheduled for completion in fiscal year 1986.)

The first step in organizing a complex technology project is to establish a technical baseline or technical description. For a project of the scale of Nova, the key to structuring a manageable baseline is to break down the technical description into smaller and smaller pieces. The result is known as a work-breakdown structure (WBS). The WBS serves as a baseline against which cost and schedule estimates are prepared.

In the Nova project, tasks were broken down into six levels (Fig. 3). Level 0 is the Nova project as a single-unit undertaking. Level 1 consists of the Nova laser itself and its two buildings (only the laser system is illustrated in the truncated example of Fig. 3). The next level, level 2, comprises laser systems such as mechanical systems. We proceed through subsystems and components to the lowest level, parts of components (level 5). The 31.5-cm-diam disk

Fig. 2

Nova project cost and schedule trends. Construction was authorized in fiscal year 1978. The eleven events show the effect on project cost and schedule of funding limitations, changes in project scope, etc.



1 Schedule slip due to fiscal year 1979 funding limitation.

2 DOE review approves ten beams only.

3 Schedule slip based on reassessment of ten-beam-only strategy.

4 Cost increase and schedule slip due to fiscal year 1981 funding limitation.

5 Preliminary DOE approval of twenty beams and harmonic conversion.

6 Cancelled DOE twenty-beam approval and reverted back to ten beams.

7 Cost increase and schedule slip due to "mark time" strategy and uncertainties about fiscal year 1982 funding and project scope.

8 Cost increase and schedule slip for addition of harmonic conversion capability.

9 Cost increase and schedule slip due to proposed fiscal year 1983 funding.

10 Cost decrease and schedule acceleration due to full funding in fiscal year 1983.

11 Schedule delay for extended Novette operations.

component shown in Fig. 3, for example, is composed of a housing, shield glass, a fluid pump, cradles and pipes, nitrogen gas, and so on.

At the outset of a project, it is not feasible to specify a technical description to the lowest level for every system; consequently, the WBS should be regarded as a tree that grows and branches during the lifetime of the project.

Once the Nova project was defined in terms of a WBS, the next step was to establish an organization, or project team, to accomplish the task. Such an organization can be structured for management purposes in several ways. One way is to match a particular group with a hardware end item, such as an amplifier. Another way is to organize tasks according to personnel skills, such as mechanical engineering, electrical engineering, and so on. Because the Laboratory's Engineering Department was already structured according to personnel skills, we elected to carry over that structure to the Nova WBS.

Having produced a technical description of the project and a WBS, our next step was to establish a one-for-one overlay for the project organization, so that an identified person was responsible for each item at each level of the WBS. That person then prepared a technical description, a cost estimate, and a schedule for his particular WBS responsibility.

Finally, to satisfy the DOE's reporting requirements, we needed some means of measuring scheduled performance against actual performance. Such a performance measuring system, called a cost and schedule control system, consists of three curves. The first two are conventional: an estimated cost curve and an actual cost curve (Fig. 4). The

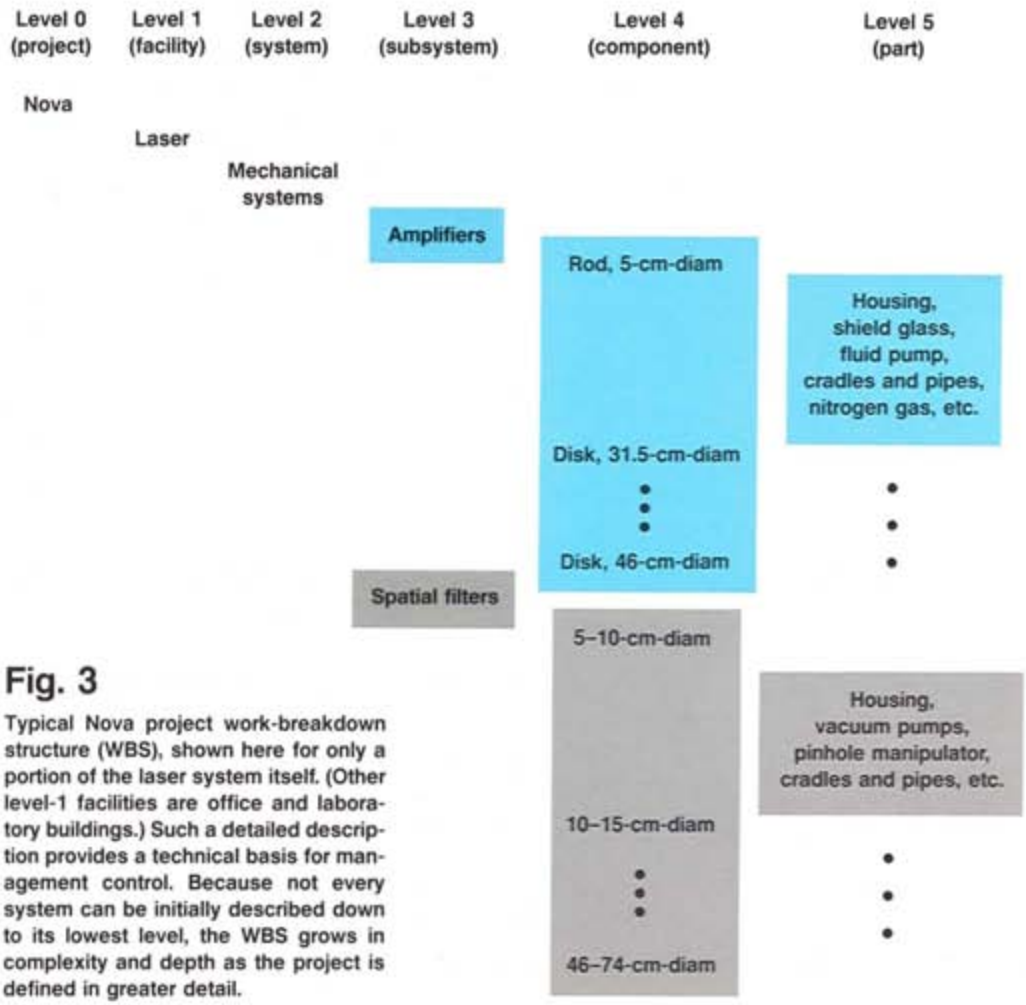


Fig. 3

Typical Nova project work-breakdown structure (WBS), shown here for only a portion of the laser system itself. (Other level-1 facilities are office and laboratory buildings.) Such a detailed description provides a technical basis for management control. Because not every system can be initially described down to its lowest level, the WBS grows in complexity and depth as the project is defined in greater detail.

Roster of Nova Vendors

Contracts awarded for more than $1 million

Raymond Kaiser Engineers
Scott Co. of California
Schott Glass Technology Inc.
Hoya Optics Incorporated
J and K Builders General Contractor
Kiewit Pacific Company
Optical Coating Laboratory Inc.
Albert C. Martin & Associates
Zygo Corporation
Cleveland Crystals
Eastman Kodak Company
Delmonte Electric Company Inc.
Spectra-Physics Inc.
C. Overaa & Company
Ferrero Electric Co.
Corning Glass Works
Bostrom-Bergen Metal Products
Digital Equipment Corporation
Weldun International
General Electric Co., Capacitor Div.
Alliance Tool & Die Corporation
Lawson Mechanical Contractors
Riverside Steel Construction
Aerojet Electro Systems Co.
Perkin-Elmer

Contracts awarded for $100,000 to $1 million

Overly/Pacific Manufacturing
Pneumo Precision Inc.
Bendix Field Engineering Corporation
Aydin Corporation
Chicago Bridge & Iron Company
Tinsley Laboratory Inc.
ILC Technology Inc.
Westinghouse Electric Corporation
Nume Oh-Hove Inc.
Adams and Smith Inc.
GCI
Helfrecht Corporation
Smith Williston Incorporated
Interactive Radiation Incorporated
Electronics Metal Finishing Inc.
Meadville Precision Tool & Molding
E. G. Smith Products Inc.
Heraeus-Amersil Inc.
Molitor Industries Inc.
Lasermetrics Inc.
Bolt Beranek Newman
Klinger Scientific Corporation
Sierra Crane & Hoist Co. Inc.
Bechtel National Inc.
Maxwell Laboratories Inc.
Ford Construction Company Inc.
Continental Optical Company
Ramtek Corp.
Meyer Tool & Manufacturing Co.
Grinnell Fire Protection Systems Co.
Christie Constructors Inc.
Penhall Company
Aero-Space Welding & Machining Inc.
Oxford General Industries Inc.
Owens Illinois Inc.
E G and G Inc.
California Engineer Contractors Inc.
CTI Cryogenics U.S. Inc.
James L. Whittaker Inc.
Best Tool Company
Hewlett Packard
C.L. Norton Co. Inc.
Gar Electro Forming Inc.
Sunset Foundry Company Inc.
Coors Porcelain Company
Madruga Iron Works
Sheller Globe Corporation
Pan American Steel
Quantronix Corporation
All Weld Machine & Fabrication Co.
Reynolds Metals Co.
Kilsby-Roberts Company
Newport Controls Corporation
Design Optics Inc.
Allied Engineering & Production Corp.
Allen Bradly Ltd.
Enterprise Roofing Service Inc.
Glass Fabricators Inc.
Angenieux Incorporated
Hugin Industries
Floating Point Systems Inc.
Kigre Incorporated
The Hughes Plastic Co. Inc.
Coleman Precision Mfg. Co.
GNB Corporation
Bendix Corporation
James Packaging Corporation
Flying Machines
Kenlab
R.C.A.
Master Metal Products Co.
Red Feather Construction Inc.
Pacific Electric Motor Inc.
Coherent Inc.
Franklin High Voltage Inc.
Caral Inc.
Kinney Vacuum Co.
Bach Machine
Adept Manufacturing Co.
Aero Design

Contracts awarded for $25,000 to $100,000

Zero Corporation
DRF Associates
Astro Model Development Corporation
L.T.I. C/O Prideaux Company
McMahon Welding Inc.
Evergreen Industries
Metal Bellows Corp.
N.A. Darcy Company
Xenon Corporation
Calorimetric Inc.
March Metalfab Inc.
A.L. Johnson Company
IKO International
Harper-Leader Inc.
Tektronix
Sohio Engineering Materials Company
IT&T Electro Optical Products Div.
Presray Corp.
Advance Engineering
Quantel International Corporation
Tube Service Company
Micron Machinery Company
Americom Electronics Corp.
Contraves-Goerz Corporation
Cardon Instruments Co.
Aerotech Inc.
Varian/Eimac
General Tool Company
Aerovox Industries Inc.
Hyspan Precision Products Inc.
Keehner Manufacturing Company Inc.
Diamond Tool Company
Abacus Electronics Company Inc.
Swenton Tool & Die Company Inc.
Applied Optics
Fisher Scientific
United Detector Technology
Champ Company
Airtron Solid State & Optical Co.
D&M Machine
Beimer Machine Works
Edwards Thomas & Company
Versatec Inc.
Balzers Corp.
Luick Quality Gage & Tool Inc.
McCarron Electric
Alpase Inc.
Cryogenic Experts Incorporated
Oracle Corp.
Plough Electric Supply Co.
Technical Fabricators Inc.
Northeastern Tool Co. Inc.
Topaz Electronics
Intrepid Enterprises
Integrated Software Co.
Aladdin Heating Corp.
Analog Device
Modern Plastics Inc.
Current Products Inc.
Western Piping
Scientech Inc.
Mac Panel Company
Stangenes Inc.
Keuffel & Esser Co.
Terminal Manufacturing Inc.
Lukas Machine Inc.
Chalet Tool Company
Apsco Manufacturing Co.
Dezurik
Dresser Industries
Kinetic Systems
Tapemation
Lord Corp Hughson Metals
Lintech Corp.
Acton Research
Math-Associates
Tom Walsh Associates
Wiegman & Rose International Corp.
Daedal Inc.
Up-Right Inc.
Aracor
Crystal Mark
Ahaus Tool Company Inc.
Oriel Corp
H-P Machinery
Equipto Inc.
Nuclear Data Inc.
Pathway Bellows
Fluorocarbon U.S. Quartz Division
Onan Corporation
Bearing Engineering

third curve, somewhat less familiar, is called the budgeted cost of work performed (BCWP).

This last curve is the key to measuring a project's progress in meaningful terms. The idea can be illustrated with a simple example. Suppose that we are building cars and estimate that we can build ten cars per month at a production cost of $10 000 each. The projected total production cost per month would then be $100 000. Let us further suppose that we know only that the total production cost for a particular month is $100 000. We might be tempted to conclude that we had precisely met our performance standard. However, we also would have to know how many cars we had built at that cost. If we had built 20 cars in a month for our cost of $100 000 (BCWP = $200 000), we would have performed very well, having produced twice the scheduled number of cars for the same production cost, halving the cost per unit. Suppose, however, that we had built only five cars in a month for our $100 000 (BCWP = $50 000); in this case, we would have performed dismally, producing only half the number of scheduled cars at double the unit cost. By enabling us to make such judgments about performance in terms of costs and schedules, then, the budgeted cost of work performed provides a meaningful measure of progress toward a goal in time.

Estimating Costs

The utility of such a technique depends, of course, on accurate cost estimates at each level of the WBS. In practice, this entails a continual refining of cost estimates for each element in the WBS as the technical description grows in detail and complexity. For the Nova project, our initial hardware cost estimates went to a depth of level 4 or 5, that is, to the component or part level. We used the cost history of the Shiva laser as a starting point, scaling the costs up or down for larger or smaller components as appropriate. We added an amount for inflation and factored in a learning curve for quantity production.

We analyzed labor costs by first estimating the time to complete a specific task and then arriving at a cumulative time to complete a budgeted item. By comparing cumulative times with actual labor costs on the Shiva project, we were able to develop a composite labor rate. Cost estimates were then made by multiplying cumulative labor time by labor rates, which have been inflated for the year of expenditure.

Together, the hardware and labor cost estimates provided a basis for financial control of the Nova project by enabling us to compare, as described above, budgeted and actual costs of work performed.

Measuring Progress

The progress of a large-scale technology project can be compared to the life of an individual: it is born, grows into childhood as it advances with learning, matures into peak productivity in adulthood, and finally enters a terminal phase to make way for the next generation of technology. Because, as in human endeavor, performance at each stage of a project is judged by different criteria, it is often necessary to shift the management focus as the project proceeds. The Nova project was divided into three phases, with corresponding management emphasis appropriate to each phase.

In the early phase of the project, characterized by design and procurement efforts, we focused on determining whether our purchase orders were being placed on time and whether actual costs were no greater than budgeted costs. If so, we knew that two things were occurring: we were completing our

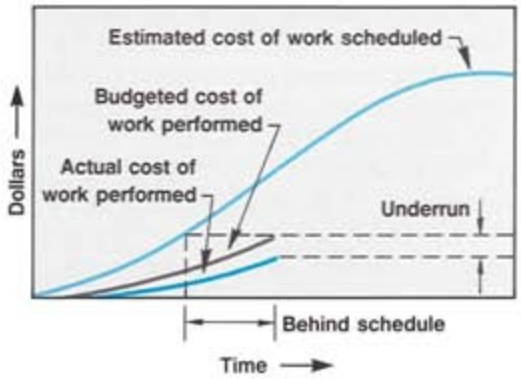


Fig. 4

The Nova project's financial planning and tracking system enabled management to measure progress against precisely specified schedule and cost goals. In this illustration, two of the curves, the estimated and actual costs (upper and lower curves) at a given point in the schedule, are conventional performance measurements. To accurately measure progress, however, we must know not only the cost of the work performed but also the amount of work. This is represented by the third curve, the budgeted cost of work performed. What appears to be good news about lower-than-expected costs can actually be bad news about performance if the project is behind schedule.

designs on schedule and our costs would be within budget.

During the second phase, as orders began to arrive, we examined how costs were accruing for the purchase orders. We normally paid on delivery; thus, if costs were being accrued as projected, we could conclude that orders were being delivered as expected.

Finally, after the bulk of the orders was delivered, we needed to shift to another index of progress. We chose to focus on the activation of the laser system. We asked such questions as whether the components of Nova's ten amplifier chains were being assembled, installed, and aligned as projected, and whether the beams were being activated on schedule.

Subcontractors

Altogether, 195 subcontractors were awarded Nova project contracts worth $25 000 or more; 25 were worth more than $1 million. As with the Shiva project, our practice was to contract out all hardware fabrication and to use contract labor rather than increase Laboratory staff to perform the same work on a short-term basis. This policy minimized manpower fluctuations within the Laboratory. Most of the hardware was procured on a fixed-price, build-to-print basis: we provided the design and contracted with a vendor to produce the item according to our drawings rather than to performance specifications. Such a policy enables a small, low-technology firm to produce a high-technology component. Here again, a detailed WBS proved invaluable; by separating a complex, high-technology system into many smaller elements, we enabled a large number of small firms to participate and also minimized the risk for each vendor (and for the Laboratory, too, by spreading the costs over many suppliers rather than over a few large contractors). All told, about 75% of the dollar value of the $176 million Nova contract was contracted out to private industry in the form of hardware procurement (see the roster of vendors with contracts worth more than $25,000, on p. 30).

In addition, a significant part of the Nova labor budget went to three companies with whom we contracted to provide on-site design and operational support for the laser system: Raymond Kaiser Engineers, the Bechtel Group, Inc., and the Bendix Field Engineering Corporation. Kaiser and Bechtel provided on-site, integrated design support, and Bendix provided on-site operational support.

DOE Review

Because of the scale of the Nova project, the SAN (San Francisco operations) office of the DOE established an on-site project office. There were weekly informal discussions of various aspects of the project with the DOE project manager. In addition, we held a monthly project review with the DOE Nova project manager. Finally, we described technical progress and reported on cost and schedule matters in great detail at one- to two-day semiannual reviews. The semiannual reviews were attended by people from the DOE Office of Inertial Fusion in Washington, D.C., from the DOE SAN office, and from our laser program. Such reviews were helpful to our own laser program management as well as to off-site personnel.

Conclusions

Capable and experienced management is a necessary but not sufficient condition for the success of a large-scale, high-technology project such as the Nova laser facility. The sufficient condition is a team of knowledgeable, dedicated technical staff who will work in harmony to achieve the project's goals. At LLNL, we are fortunate, indeed, to have retained with relatively low turnover a large team of highly skilled specialists who have worked together on high-technology laser systems for more than a decade. The effectiveness of such teamwork has been demonstrated by the successful completion and operation of the Argus laser, the Shiva laser, the Novette laser, and now the Nova laser.

Key Words: budgeted cost of work performed; inertial confinement fusion (ICF); laser—Argus, Cyclops, Janus, Nova, Novette, Shiva; project management; work-breakdown structure.

Neodymium-Glass Laser Research and Development at LLNL

More than a decade of research and development in inertial confinement fusion (ICF) at LLNL has culminated in the Nova laser system, the most energetic and powerful neodymium-glass, solid-state laser constructed to date. The Nova laser, like its predecessors, will be used for research on nuclear-weapon physics and military applications. Experience gained with this laser will also support the ultimate goal of inertial confinement fusion—the cost-effective, central-station generation of electric power. A review of the ICF program at LLNL and the development of neodymium-glass laser systems is presented for the occasion of the initial operation of the Nova laser.

Contact: W. F. Krupke (415) 422-5354.

Nova Laser Technology

The Nova laser system is a powerful new tool for studying both the physics of nuclear weapons and inertial confinement fusion. It provides output at 50 to 100 kJ at three different wavelengths (1.05, 0.53, and 0.35 μm) and operates over a range of pulse durations from 0.1 ns to greater than 100 ns. The Nova laser will be used to verify models that describe the interaction of short-wavelength laser light with large-scale plasmas, to compress deuterium-tritium fusion fuel to densities approaching 200 g/cm^3 (1000 times the density of liquid deuterium-tritium), to extend soft-x-ray laser technology, and to advance our understanding of high-temperature and high-pressure physics for a variety of weapons and physics applications. The ultimate goal of the Laboratory's inertial-confinement fusion program is to produce, for military and civilian applications, thermonuclear microexplosions that release several hundred times more energy than the laser delivers to the target.

Contact: John F. Holzrichter (415) 423-7454.

Building Nova: Industry Relations and Technology Transfer

Technology transfer has been an integral part of LLNL's laser program since its beginnings in the early 1970s. The Laboratory's active commitment to work with U.S. industry to develop the necessary technology has ensured that the stringent demands of laser designers could be met by the companies supplying the components for increasingly powerful laser systems. The interaction of LLNL and the industries that took part in the building of the Nova laser illustrates the three basic ways of transferring technology: transferring an entire technology package, providing specific technical knowledge in a fairly narrow area, and collaborating with industry to develop a technology. The latter, with the Laboratory and a company working together and sharing the costs, is the easiest and most beneficial and was used extensively in the building of the Nova laser. Examples include technological developments that made possible the production of very large, pure crystals for harmonic conversion of laser light, large optical materials of high quality, special flat-lapping machines for polishing large-size optics pieces, and the special optical coatings required by Nova's large optical system. The result of this close collaboration was the delivery of the Nova hardware on schedule and within specifications plus a concomitant significant increase in the technology and production capability of U.S. industry.

Contact: Robert O. Godwin (415) 422-5548.

Managing the Nova Laser Project

The Laboratory's Nova laser, the latest in its evolutionary series of large research lasers, began operation in February 1985. An undertaking the size and complexity of the Nova project requires detailed organization and close monitoring of costs and schedules. This was achieved, in part, by dividing the project into many smaller elements. Because much of the work was subcontracted, it also was necessary to coordinate the contributions of over a hundred vendors, many of them small firms. Despite inflation, fluctuating annual funding levels, and major technical modifications, the project was completed on schedule and within costs.

Contact: Robert O. Godwin (415) 422-5548.

Recent Titles

Articles published in recent issues of the *Energy and Technology Review* are grouped below according to their chief sponsors, the Assistant Secretaries of the U.S. Department of Energy. Research funded by other Federal agencies is listed under Work for Others.

ENERGY RESEARCH

Fissile Fuel from Fusion (January 1985)
MARS: The Mirror Advanced Reactor Study (November 1984)
Uranium Resources and the Development of Fission and Fusion Breeder Reactors (October 1984)
Climatic Warming and Carbon Dioxide (September 1984)
Response of Plants to Increased Carbon Dioxide (September 1984)

DEFENSE PROGRAMS

Development

Transition Radiation Produces Coherent X Rays (Brief—January 1985)
Initiation Studies of TATB-Based High Explosives (December 1984)

Inertial Fusion

Building Nova: Industry Relations and Technology Transfer (February 1985)
Managing the Nova Laser Project (February 1985)
Neodymium-Glass Laser Research and Development at LLNL (February 1985)
Nova Laser Technology (February 1985)
The Novette Laser Facility: A Step in the Evolution of High-Power Laser Systems (January 1985)
Lasing Achieved at Soft-X-Ray Wavelengths in the Laboratory (Brief—January 1985)

Military Application

Electromagnetic Coupling of High-Altitude, Nuclear Electromagnetic Pulses (November 1984)
New Radiation Dosimetry Estimates for Hiroshima and Nagasaki (November 1984)
Supracompression of High-Explosive Detonation Products (October 1984)

LABORATORY REVIEWS

Mortality Among the Employees of Lawrence Livermore National Laboratory (December 1984)
Charting Our Course (December 1984)
Entering the World of Multiprocessing (October 1984)
Earthquake Safety at LLNL (August 1984)
Geology of the Livermore Valley (August 1984)
Monitoring Groundwater Quality at Site 300 (August 1984)
State of the Laboratory Issue (July 1984)

WORK FOR OTHERS

Defense Nuclear Agency

Simulating Nuclear Cratering Events at the Pacific Proving Ground (September 1984)

Nuclear Regulatory Commission

Earthquake-Hazard Analysis for Nuclear Power Plants (June 1984)
Human Factors in Reactor Facility Design (June 1984)
Reactor-Coolant Piping: Realistic Failure Assessment (June 1984)