LLNL 1981: Technical Horizons

The Lawrence Livermore National Laboratory was established in 1952 to conduct nuclear weapons research for the U.S. Government. Today, most of our work is done for the Department of Energy, and our staff has grown from the original few hundred to more than 7300 people. The scope of our research activities has also grown. Nuclear weapons research remains the single largest program, but we have also become deeply involved in inertial confinement fusion, magnetic fusion energy, applied energy technology, and biomedical and environmental sciences. Our work is extending horizons in these fields and many more.

Nuclear weapons that shield us from attack are deemed essential to the defense of the country. The development of nuclear weapons is a continuing process as research reveals new possibilities, as worldwide developments dictate new requirements, and as countermeasures reduce the effectiveness of existing weapons. The task of developing these weapons, including laying the necessary scientific groundwork and understanding the phenomena of nuclear explosions, demands a wide spectrum of resources and skills drawn from scientific, engineering, and technical disciplines. LLNL has the breadth of expertise to function productively in this demanding area.

The energy produced in thermonuclear weapons is, in large part, the energy of thermonuclear fusion. One way of producing and studying fusion reactions in a controlled environment is to bring a tiny deuterium-tritium fuel pellet to very

high temperatures and densities in such a short time that the thermonuclear fuel will ignite and burn before the compressed core disassembles. This technique, known as inertial confinement, relies upon a driver (e.g., a laser) to deliver the extremely high-power, short-duration burst of energy required.

Our inertial confinement fusion (ICF) program has both civil and military goals. The main civil application would be in the production of electricity. The military applications (far more easily realized) have to do with obtaining data on nuclear weapons physics and creating a source of radiation to simulate the effects of nuclear weapons on military hardware (recently vehicles, missiles, and satellites), all without having to conduct an actual nuclear test. Under a comprehensive ban on nuclear testing, ICF activities would be vital, enabling us to continue our studies of important and challenging diagnostics problems and to recruit and train new generations of weapons experts.

There are other ways of controlling fusion reactions. One approach is to rely upon specially shaped magnetic fields to confine the thermonuclear fuel while heating it to fusion temperatures by some external means. LLNL is conducting a vigorous magnetic fusion energy (MFE) research program, with the goal of developing the technology needed to harness thermonuclear fusion for power production. Successful development of a fusion reactor would give us practical access to fuels—deuterium (from water) and lithium—that will last for millennia.

Good progress is being made in our effort to apply lasers to the separation of isotopes. This effort has been extended to include both defense applications and the enrichment of uranium for power reactor fuel.

We are continuing our efforts to develop such applied energy technologies as coal gasification and underground retorting of oil shale. LLNL has played a major role in the Department of Energy's program to investigate coal gasification—the underground conversion of coal into clean burning gases—as a promising prospect for an environmentally acceptable way of tapping our huge coal resources. We have also worked for several years to develop an *in situ* process for recovering oil from shale. Even though obstacles to large-scale development such as environmental impacts and institutional barriers have prevented developments that are now technically and economically feasible, oil shale remains a potentially valuable energy resource.

In our biomedical and environmental sciences program, we are exploring the sources of energy-related pollutants (both nuclear and nonnuclear), their methods of transport, and their effects on plants, animals, and humans. Studies range from probes into the intimate workings of human cells to extensive surveys of entire ecosystems.

The major research programs at LLNL require various internal support organizations. These organizations, defined for the most part in terms of areas of technical

specialization (chemistry, physics, engineering, computation, etc.), keep pace with developments in the various disciplines and provide pools of well-trained professionals capable of lending their expertise to the new and constantly changing technical problems faced in the major research programs. The Laboratory's support organizations carry on sophisticated theoretical and experimental projects, many of which have applications that serve not only the major LLNL programs but the interests of the broader technical community as well.

The fulfillment of Laboratory commitments and programs requires the timely availability of programmatic resources in personnel and material. The efficient handling of these resources is supported by various administrative departments and divisions coordinated through five managers under the aegis of an associate director responsible for administration.

This issue of the *Energy and Technology Review* explores the technical horizons being defined by LLNL researchers in both support and programmatic roles. Featured first is a summary of the annual State of the Laboratory address presented by the Director, Roger Batzel, on budgetary trends and the prospects for the future. Next is a sampling of achievements, grouped under the three headings of national defense, energy and the environment, and support projects. □

The State of the Laboratory

In his annual State of the Laboratory address, Director Roger Batzel projected a \$481 million operating budget for fiscal year 1982, up nearly 13% from last year. He attributed this solid funding support to a shift in attitude at the national level and to skillful program planning and excellent staff performance over the years.

Director Roger Batzel presented his State of the Laboratory address on June 11, 1981, unveiling a proposed \$642 million total budget and a \$481 million operating budget for fiscal year 1982. This budget provides for about a 13% increase in both budget categories (see Tables 1 and 2). When 10 to 12% is subtracted for inflation, this represents a slight increase in purchasing power. Batzel emphasized that the cuts suffered by a few programs are more than offset by substantial increases in many others. He also pointed out that these figures are tentative, subject to final approval by Congress.

The largest single allocation from the Department of Energy is for weapons research. It embodies the biggest increase in this area since the Russians broke the moratorium on nuclear testing in 1961. Inertial confinement fusion remains the second largest program at the Laboratory, even though funding has been somewhat reduced. Magnetic fusion energy will see a considerable increase in funding, as will our two laser isotope separation programs—advanced isotope separation and special isotope separation—reflecting the excellent technical results achieved to date in all these programs. Funding for most other Laboratory programs is substantially increased. The biomedical and

environmental program will see only slight increases from the DOE, for the second consecutive year. When the three DOE entities in this area are broken out by program elements at the Laboratory, they show modest growth except for environmental sciences, which will sustain a reduction in staffing.

Dr. Batzel noted that the proposed 1982 budget reflects the change in administration and the associated shift in attitude at the national level. When asked about the mood in Washington, D.C., Batzel stated that the emphasis on weapons research began during the latter years of the Carter administration and is being heightened by the new administration as the result of an evaluation of the military position of the U.S. in the world and a recognition that nuclear weapons are a fundamental part of our defense posture.

Dr. Batzel commented briefly on how some of the programs will fare under the proposed 1982 budget. Although inflation will blunt the impact of all increases in funding, the \$33 million increase for weapons work will produce growth that will be of long-term benefit both to the program and to the nation. The Laboratory continues to be committed to developing warheads for new weapons systems. The budget increase will put us in

Table 1 Total financial activity, millions of dollars

	Revised FY 1981	Proposed FY 1982
Operations	\$426.8	\$481.1
Equipment	33.8	42.1
General plant	4.4	5.4
Construction	103.9	113.1
Total	\$568.9	\$641.7

Table 2 LLNL program funding, millions of dollars.

	Revised FY 1981	Proposed FY 1982
Defense programs		
Weapons	178.9	212.3
Inertial confinement fusion	55.7	45.5
Verification and control	8.6	10.1
Safeguards and security	0.9	0.6
Isotope separation	10.1	15.8
Defense waste management	3.3	3.8
Fossil energy		
Coal gasification and gas recovery	2.6	3.7
Oil shale	3.0	3.4
Gas stimulation	2.1	1.5
Conservation and renewable energy		
Solar technology and application	1.5	0.7
Transport energy conservation	0.3	0.6
Energy storage systems	5.9	4.4
Geothermal	1.0	0.6
Energy research		
Magnetic fusion	31.0	41.5
Magnetic Fusion Computer Center	9.9	12.0
Energy research	4.0	4.5
Health and environmental research	9.2	8.6
Nuclear energy		
Advanced isotope separation technology	18.9	23.3
Commercial nuclear waste	4.6	6.0
Environment, protection, safety, and emergency preparedness		
Environmental activities	1.9	2.0
Liquefied gaseous fuel programs	3.7	4.5
Other Department of Energy	11.0	13.1
Reimbursable programs and work for others	55.7	62.1
Total	426.8	481.1

a better position to test these warheads to ensure that they will indeed function as designed when incorporated into the nation's stockpile. The number of tests conducted at the Nevada Test Site in fiscal year 1982 is expected to increase over that in 1981. Advanced weapons development will benefit from the increased funding and the increased testing, enabling us to explore new concepts that have never been tested because of limited resources.

We have received approval to purchase two additional Cray computers, which will be installed in December 1981 and May 1982 and will provide a significant improvement in our computational capability.

Batzel expressed pleasure at the solid support on a national level for the Laboratory's programs in magnetic fusion energy. In his opinion, fiscal year 1981 was a banner year for these programs, and this support is well deserved. The Tandem Mirror Experiment produced encouraging results, and the Magnetic Fusion Test Facility, currently under construction, will be a unique experimental resource. Batzel asserted that the magnetic mirror approach to magnetic fusion is a solid alternative to tokamaks and noted that there is a good possibility that the magnetic mirror approach will be the one chosen for the first demonstration facility.

In discussing the several programs and subprograms that face restricted budgets in 1982, Batzel recognized that there is only a limited amount of money available for programs like the Laboratory's. In effect, it is a "zero-sum game," where increases in some programs must come at the expense of others.

Regarding inertial confinement fusion (laser fusion), Batzel noted that, although the program had many solid achievements during the past year, a decision was made by the government to reduce funding in this area in the belief that some cuts could be achieved without serious consequences. Batzel stated that, in his view, these cuts should cause only a temporary slowdown. He noted that the House Armed Services Committee has proposed additional funding to correct the situation, although it is uncertain whether this item will survive the remaining legislative action.

Batzel pointed out that the limited funding in environmental sciences reflects the feeling in parts of the new administration that environmental issues have received too much emphasis in the past. These cuts reflect a decision to limit support in this area until the situation is reevaluated. In this case, also, he views the reduced funding as a temporary situation. He noted that biomedical sciences has survived intact—a good decision, in his opinion.

The *in situ* coal gasification program shows a modest increase in fiscal year 1982. Batzel stated that he believes the Laboratory has an important role to play here over the next several years. In the long term, of course, this program will be turned over to industry. In Batzel's view, the Laboratory's role should be to make technological advances that will provide industry with the necessary confidence to invest its own money for commercial-scale development.

In summary, Batzel noted that the Laboratory's budget is increasing slightly at a time when other federally funded institutions are facing cuts. He projected a staff increase of 150 people which, with replacement for normal attrition, means about 1000 new hires in fiscal year 1982. Reassignments will be available for those persons affected by decreases in programmatic budgets.

Batzel stated that growth at this time reflects both the increased attention being given to defense issues in general and the Laboratory's history of technically solid programs. The programs at the Laboratory are the kinds that will continue to be supported by the Federal government because of the long-term, essential nature of the work. In his opinion, this is a proper role for the Laboratory.

Batzel then discussed some of the problems facing the Laboratory in fiscal year 1982. The major problem continues to be inadequate facilities. There are nearly one thousand temporary trailers on site, evidence of the need for more permanent office space. There is also some lack of laboratory space. We have been reasonably successful in getting new construction in the past few years, most of it in the form of laboratory facilities but also including the Core-1 office building, the

new office building for the magnetic fusion program, and the office addition associated with the Nova laser fusion facility. Batzel noted that the House Armed Services Committee has proposed additional funds for two new construction projects—the weapons materials research and development facility and the high-explosive applications program facility.

Regarding the status of the new five-year contract (due to start October 1, 1982) between the U.S. Department of Energy and the University of California for management of the two weapons laboratories, Batzel explained that in their May 1981 meeting, the Regents decided more time was needed to study the proposed contract thoroughly. Consequently, the vote on accepting the contract was delayed until the June meeting. [Editor's note: On June 19, the Regents approved the contract and delegated to President Saxon the authority to sign it.]

On the subject of collective bargaining, Batzel noted that the earliest we could expect an election would be late 1981 or early 1982. Myriad issues must first be resolved—such as defining bargaining units and determining who are the supervisors. Batzel reaffirmed his belief that collective bargaining is not in the best interests of the Laboratory or of the people within the Laboratory. "The existing relationship is a good one. It has proved successful. I don't want to disrupt it because, in the long term, that would be very detrimental to the Laboratory."

In closing, Dr. Batzel emphasized that, all in all, the Laboratory will fare very well in fiscal year 1982. The increasing budget looks especially good when compared with budget cuts faced by many other government institutions. He concluded that the Laboratory's favorable position is a direct result of skillful program planning and excellent staff performance over the years. "We are an applied technology laboratory, we've chosen and conducted our programs well, our results are good, and thus we're viewed at the national level as a successful laboratory." □

Nation

From the beginning, the Laboratory's main function has been to contribute to the development and maintenance of a stockpile of nuclear weapons capable of deterring any potential aggressor.

LLNL was established as and continues to be predominantly a nuclear weapons design laboratory, but over the years our expertise has been called upon in other areas of defense research as well: inertial confinement fusion (the production of fusion reactions by means of short, intense pulses of laser or particle-beam energy), nonnuclear ordnance (which requires many of the same technical facilities and capabilities as nuclear weapons research), and particle-beam technology.

Our nuclear weapons and inertial confinement fusion work is funded by the U.S. Department of Energy (DOE); the nonnuclear work is conducted under the auspices of the Department of Defense (DOD). We will discuss the LLNL program under two broad headings: Defense Programs (DOE) and Defense Projects (DOD).

Defense Programs (DOE)

Nuclear Weapons

The nuclear weapons effort at LLNL involves three programs: nuclear design, nuclear testing, and military applications.

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The goal of the nuclear design effort is to explore advanced weapons concepts and to improve our understanding of weapons physics. The nuclear test program has responsibility for fielding device tests at the Nevada Test Site. (This includes the design and construction of the downhole canister, shown on this page, and the design and fielding of diagnostic equipment.) The military applications program is charged with developing a modern, reliable nuclear stockpile, initiating studies relating to the usefulness of nuclear weapons, and maintaining the current stockpile.

Nuclear design. Knowing what is possible in nuclear weaponry is important because it prevents our being surprised by a potential adversary. We are currently working on advanced designs that further enhance the safety and security of weapons and that tailor nuclear effects for specific purposes.

Nuclear designs that provide added safety also enhance security (e.g., by preventing the misuse of an illegally obtained weapon). Modern designs contain insensitive high explosive (IHE), which virtually eliminates the possibility of an accidental HE detonation due to impact or exposure to high temperatures. This, in turn, minimizes the likelihood of an accidental scattering of hazardous material. Some designs have separate vaults with layers of refractory material to contain the fissile material safely even if it melts.

Another recent development is the mechanical safe and arm detonator (MSAD), which operates by driving a thin aluminum flyer plate into a charge of IHE. Until it receives a 24-bit coded signal (after launch), the MSAD withholds the high-explosive pellet that drives the flyer plate. Thus, the detonator is safe throughout its lifetime. MSAD can either augment or replace other safety devices used previously.

Fig. 1

A schematic representation of seismic-reflection mapping of subsurface geology. A truck-mounted vibrator sends a low-frequency sound signal into the ground, and a series of geophones detects the echoes. By combining information from a series of such measurements recorded at different locations, we can deduce the shapes of subsurface layers.

The accrued results of our theoretical investigations during recent years have laid the ground work for experimental and developmental programs to follow.

New weapons also contain effective disablement features that can be activated manually or automatically. This makes it very unlikely that an unauthorized person would ever obtain an intact, detonable nuclear weapon. Weapons with still more advanced safety features are under investigation.

We are working on designs that minimize fallout and blast in relation to prompt radiation. Tailored effects of this kind make it possible to achieve specific military objectives while minimizing the collateral damage in surrounding communities and nonmilitary installations.

In recent years, the testing of advanced nuclear devices has proceeded at a very slow pace, partly because the overall number of tests has been low and partly because most of the tests have been needed for designs that had reached the development engineering phase in anticipation of introduction into the stockpile. However, we have made progress in several key areas of advanced design, particularly in theoretical investigations.

The next several years offer a much brighter outlook for advanced development. As current weapons engineering development programs mature, their testing level will decline, and, at the same time, the overall number of tests is expected to increase. These shifts should make possible a period of high achievement in advanced design work. Thus, the accrued results of our theoretical investigations during recent years have laid the groundwork for experimental and developmental programs to follow.

Nuclear testing. Nuclear testing involves far more than installing a device in a hole and detonating it. There is, for example, the challenging problem of measuring significant explosion

phenomena in many different ways in the brief period of time available in an adverse environment far from conventional services. To meet this challenge, we are constantly developing new diagnostic instruments and techniques and upgrading our technology base. Much of this upgrading comes as a result of developments in private industry. However, where our requirements are unique, we ourselves develop the necessary new technology.

Microprocessors are having a major impact on new instrumentation systems. They allow us to make instruments that calibrate and troubleshoot themselves, monitor their own output, adjust to changing conditions, and operate unattended for extended periods. We are applying this technology to provide faster setup and more comprehensive and reliable system checks and to free our staff for more challenging and constructive tasks. In our control room at the Nevada Test Site, interactive graphics and alarm, control, and monitoring software afford us increased reliability as we conduct nuclear tests.

Another microprocessor-based system operates equipment in our X-ray Calibration and Standards Laboratory. This physics-information-gathering system allows us to use multichannel analyzers and acquire data without having operators in constant attendance. The system gives us more and better data, while sparing our technicians many hours of repetitious work.

We have recently begun to make use of wide-band fiber-optic cables to transmit high-speed data from new diagnostic systems on nuclear tests. Because they are nonconductive, fiber-optic materials transmit the signal more clearly (without electromagnetic noise). This improves the quality of data from present measurements, permits us to make new kinds of measurements, and reduces costs.

In planning our Nevada tests, we must avoid drilling emplacement holes in areas that are geologically unsuitable. Therefore, we are adapting seismic-reflection surveys (now in routine use in the mining and petroleum industries) to the special needs of the test program (Fig. 1). The Nevada Test Site, with its relatively thick and complex layer of

alluvium, poses special problems for this technology, but we have made considerable progress in coping with them. In the past year, we have begun to generate useful and reliable maps of the test site's subsurface geology.

In our continuing effort to evaluate the yield of nuclear devices by radiochemical means, we are placing increasing emphasis on analyzing gaseous materials, particularly the isotopes of hydrogen, helium, neon, krypton, and xenon. Because most of the informative isotopes of these elements are nonradioactive, we measure them by means of mass spectrometry. We have installed two new mass spectrometers, which we are now using routinely on nuclear test samples. They provide high sensitivities and improved accuracy.

Recent developments allow us to produce traveling-wave cathode-ray oscilloscope tubes with greatly improved bandwidths. This advance was made possible by (a) the discovery of ways to install microchannel plates within the evacuated cathode-ray tube and (b) new enhanced phosphors that allow finer spot size and better definition.

At the Nevada Test Site, we often need to examine either the equipment or the rocks deep in a hole or to work on downhole equipment. To permit such operations, we recently placed in service a

Fig. 2

Drone, a remote-controlled robot camera for inspecting equipment and the downhole environment in nuclear-test emplacements. Drone can be fitted to provide stereo documentation photographs or live closed-circuit TV pictures. It is also equipped to perform certain mechanical manipulations.

flexible robot package that allows stereo viewing. This package (Fig. 2), called Drone, can be lowered to provide television viewing, stereo and movie photography, and some downhole manipulation.

At Mercury, Nevada, we are building a facility in which to assemble and test downhole tools. It includes a hole 3 m in diameter and 36 m deep that provides a realistic environment in which to check tools and instruments used in geophysical logging.

We are also pursuing an entirely new technique for suspending the many electrical and signal cables used in a nuclear test. A computer-controlled mechanical tensioner speeds the emplacement of the nuclear device and its diagnostic equipment. Our current procedures call for the attachment of the electrical cables to the emplacement pipe at frequent intervals (to

maintain the proper tension). This requires much manpower and time (6 to 12 days). With the new system maintaining proper cable tension throughout the lowering operation, we should be able to suspend each cable from the surface, reducing downhole time to 1 or 2 days and saving perhaps \$2 million per year.

Military applications. LLNL is charged with the responsibility of developing warheads for existing or proposed weapons-delivery systems, maintaining the existing stockpile, and evaluating the uses and effects of various weapons systems.

There are seven phases to the nuclear weapons life cycle: conceptual studies, feasibility studies, development engineering, production engineering, first production, quantity production and stockpile maintenance, and retirement.

During the past year, we have concluded a feasibility study on warhead designs for a Trident-launched evader vehicle and on a warhead for the MX Advanced Ballistic Reentry Vehicle. (The development schedule for these systems has not been decided.) We have also participated in a conceptual design study for a tactical air-to-ground missile.

With others in the ballistic missile defense community, we are working hard on ideas for a low-altitude defense system for the MX missile. Another feasibility study, for an upgraded antisubmarine-warfare capability, is prompted by the evolution of Soviet submarine speed and operational-depth capability.

LLNL warhead projects that have progressed beyond the conceptual design and feasibility stages are summarized in Fig. 3. Each poses unique challenges to the designers. The B83 strategic bomb must have rugged structural characteristics because in one of the delivery modes it is dropped by low-flying aircraft on hard, irregular targets. The W79 and W82 artillery shells must be capable of withstanding enormous launch loads, and both must have ballistic properties comparable to those of nonnuclear rounds (so that the artillery can zero in on a target with conventional ordnance before the nuclear round is fired). The new Lance missile warhead (W70-4) must add new

tactical capability to the missile system, as well as modern command and control systems, without altering the flight dynamics of the missile used for the W70-1 and W70-2. The W84 ground-launched cruise missile warhead must incorporate many recently developed safety and security features that make it suitable for deployment in Europe. The W70-4 and the W84 represent new weapon capabilities. The W79, W82, and B83 are being designed to replace weapons of lesser capability that have been in the stockpile for more than 20 years.

As Fig. 3 illustrates, there was a burst of new development engineering projects in 1978-1979, but no additional projects have been authorized for more than two years. We are pleased that this decreasing development engineering work load, together with increasing weapons program resources, offers the prospect for a better balance between advanced development and development engineering.

Our responsibility for nuclear warheads does not end with production. We must also monitor and evaluate their reliability after they enter the stockpile. During the past year, as part of this effort, we conducted an underground nuclear test of a W68/MK3 ALT 304 warhead randomly selected from the production line. This stockpile-confidence test successfully demonstrated the nuclear performance of the newly retrofitted W68 warhead for the Navy's submarine-launched Poseidon missile system. It also permitted us to obtain modern prompt diagnostics on this system's performance.

Over the past year, we have made an overall analysis of the W70 stockpile-evaluation program, concluding that it is unnecessarily stringent. We therefore reduced the sampling and testing requirements, effecting a saving in money and a reduction in the number of withdrawals from the W70 stockpile.

In support of the weapons design effort, steps have been taken this year to enhance engineering design and test facilities at LLNL. We have received authorization to build a thermal test building and an electrodynamic exciter building and to purchase associated test equipment. This \$3.3 million project is the first phase of a

planned \$8.6 million, five-building project that will bring our engineering test facilities up to date and greatly facilitate warhead development work.

During the past year, we have brought into full operation a computer-aided design and drafting (CADD) system that can automatically rotate parts and move them about (on a display screen), provide isometric drawings, obtain surface intersections, pass cut planes through parts, and calculate mass properties. It reduces the initial design time, produces layouts and detailed drawings much faster, and helps us detect errors earlier. We have also procured a computer-controlled lathe and mill, which eventually will be linked to the CADD equipment, greatly simplifying and speeding the fabrication process.

One aspect of the military applications program that transcends pure engineering is planning and evaluation to determine how given weapons systems might be used and with what result. During the past year, we have developed and applied JANUS, a greatly improved two-sided interactive combat-simulation code for modeling an integrated (nuclear/chemical/conventional) battlefield (see box, p. 14).

Another aspect of the military applications program is illustrated by recent dosimetry studies of radiation exposure at Hiroshima and Nagasaki. Data on the radiation exposure of survivors of the Hiroshima and Nagasaki atomic bombs are a vital factor in the development of international protection standards for nuclear radiation. These data have been thought to be particularly valuable for this purpose because of the large neutron component of the initial radiation that was believed to have been present at Hiroshima (as compared to other available exposure data). However, the value of these data is limited by the accuracy with which the radiation dose of each individual survivor can be specified. Since 1965, this specification has been based on the T65D (tentative 1965 dose) pattern of neutron and gamma-ray dose estimates for all distances of interest at Hiroshima and Nagasaki.

We have made new free-in-air dose estimates that show changes in dose as large as a factor of nine and reduce the

W82

Fig. 3

LLNL warhead projects currently under development or in production engineering. In FY 1981, the Laboratory will spend \$156 million on weapons projects.

B83: Modern strategic bomb
Authorized: January 1979
Status: Production engineering

W70-4: Lance surface-to-surface missile
Authorized: October 1978
Status: Initial production, May 1981

W79: 8-in. howitzer projectile
Authorized: January 1975
Status: Initial production, July 1981

W82: 155-mm howitzer or cannon projectile
Authorized: February 1978
Status: Development

W84: Ground-launched cruise missile
Authorized: October 1978
Status: Production engineering

Fig. 4

The Nova laser fusion research facility, now under construction, will provide researchers with powerful new tools for the study of nuclear weapons physics and inertial confinement fusion. This figure shows blanks for Nova's first five turning mirrors. These high-quality, 1.2-m mirrors eventually will direct Nova's 20 large (74-cm diam) beams for a few billionths of a second to a tiny pellet containing thermonuclear fuel (deuterium and tritium). Explosive ablation of the outer layers of the fuel pellet will drive an implosion that is expected to compress the fuel to a thousandth or less of its original volume and heat it to thermonuclear-ignition temperatures.

Fig. 5

Laser fusion becomes easier at shorter wavelengths. This graph shows the improvement in absorption of laser light and in the conversion of absorbed laser light into low-energy x-rays (0.1 to 1.8 keV) that is possible using the first and second harmonics of the infrared light (wavelength 1.06 μm) generated by our neodymium-glass lasers. We used potassium dihydrogen phosphate (KDP) crystals to double and triple the frequency of the light to wavelengths of 0.53 and 0.36 μm, respectively, a conversion that we have demonstrated on the Argus laser system to be 75% efficient.

proportion of neutrons at Hiroshima by as much as a factor of thirty-six. Major new elements in our approach include the use of the most current calculated bomb output spectra from Los Alamos National Laboratory, an evaluation and modeling of gamma-ray dose from bomb debris measured in field tests, our own air-transport calculations, and evaluation of all these elements, as well as comparison with, and reinterpretation of, prior *in situ* measurements.

As an example of how our new dose estimates affect the interpretation of atomic bomb survivor data, leukemia mortality data distributed according to the earlier dosimetry showed strong differences between the two bombed cities, suggesting large values of neutron RBE (relative biological effectiveness), whereas the same mortality data distributed with the new dosimetry show no discernable differences between the two cities.

Inertial Confinement Fusion

The energy of a modern nuclear weapon is in large part the energy of thermonuclear fusion. One way of producing and studying fusion reactions and related physics in a more controlled environment is to bring a tiny deuterium-tritium (D-T) fuel pellet to very high temperatures and densities in such a short time that the thermonuclear fuel will ignite and burn before the compressed core disassembles. This technique, known as inertial confinement, relies upon a driver (e.g., a laser) to deliver the extremely high-power, short-duration burst of energy required.^{1,2}

Inertial confinement fusion (ICF) has potential for civil applications, mainly in the production of electricity, and military applications directed toward obtaining

data on nuclear weapons physics and creating a source of radiation to simulate the effects of nuclear weapons on military hardware without having to conduct an actual nuclear test.

A power-producing fusion reactor would require lasers that deliver up to 10 pulses per second, each pulse capable of imploding a D-T target to 1000 or more times the density of liquid hydrogen and igniting a thermonuclear reaction that releases more than 100 times as much energy as the laser delivers to the target. Our Nova laser system (Fig. 4), now under construction and scheduled for completion in the mid 1980s, is expected to deliver (in single pulses) 200 to 300 kJ of 1.06- μm light or 140 to 200 kJ of 0.35- and 0.53- μm light to compress its fuel capsules to 1000 times liquid density and ignite a thermonuclear reaction that releases about as much energy as the laser delivers to the target. Although the Nova laser represents a significant step toward a fusion power reactor, that goal is still a distant one.

During 1980, our Shiva laser system, operating at 6 to 8 kJ in single 500- to 800-ps pulses (with 1.06- μm infrared light), successfully imploded specially designed D-T fuel capsules to more than 10^3 times the density of liquid hydrogen (in excellent agreement with preshot calculations). Both the density attained and the agreement with calculations are significant as indications of our progress.

Perhaps even more significant was our demonstration on the Argus laser that we could convert 1.06- μm light into 0.53- and 0.36- μm light (green and ultraviolet, respectively) at efficiencies of 75% and our experimental confirmation of excellent laser-plasma coupling at these shorter wavelengths. Figure 5 shows the significant theoretical and observed increase in the absorption of laser radiation at 0.53 and 0.36 μm and the equally dramatic change in the soft-x-ray conversion efficiency. Figure 6 shows the resulting many-orders-of-magnitude reduction in hot-electron and superthermal-x-ray production.

These results indicate that the implosion-driving conditions in targets irradiated with green or ultraviolet light will be significantly better than those in

Fig. 6

Superthermal x-ray spectra, extending far beyond the thermal x-ray spectrum normally associated with a plasma at the measured temperature, observed in irradiations of gold disks at about 300 TW/cm^2 , about the intensity required to drive future targets to ignition. Hot electrons, of which the superthermal x rays are evidence, interfere with the implosion by penetrating the fuel pellet and preheating the fuel. That we are able to reduce this hot-electron preheat by a factor of almost 10 000 (by changing from infrared light to ultraviolet) has profound and very positive implications for the amount of compression to be expected from Nova target irradiations.

Results indicate that the implosion-driving conditions in targets irradiated with green or ultraviolet light will be significantly better than those in the same target irradiated with infrared light.

the same target irradiated with infrared light. The inward-directed forces will be larger, and the stiffening effects, which tend to make the capsule resist implosion (e.g., preheating by energetic electrons), will be smaller.

A screen display from JANUS, an interactive combat simulator potentially capable of encompassing an entire Corps operation, showing the disposition of the Blue forces (colored symbols) near the confluence of two rivers. JANUS offers three unique features that make its simulations more realistic and believable than those of previous models. It gives players push-button access to different levels of resolution, enabling them to view the entire sweep of an attack or to concentrate on such details as individual tank battles. It achieves this capability partly by using variable-size zoning: and partly by treating units *en masse* most of the time. Only when units are engaged in combat does it resolve them into their component subunits for shot-by-shot resolution of the conflict. It also provides for different levels of command, giving lower ranks a restricted but detailed view and reserving the broader picture for the higher echelons.

JANUS

JANUS is a greatly improved two-sided interactive combat-simulation code for modeling an integrated battlefield. Previous computer models, simulations, and games have had limited success in portraying the real problems of combat command. As a result, many users and decision-makers have been understandably reluctant to accept their recommendations.

Three key techniques implemented in JANUS during the past year, together with the use of real-time dynamic color graphics of high resolution (figure), have contributed to a high level of acceptance of this code. The first of the new techniques involves terrain resolution—mapping a battlefield in enough detail to show individual tank encounters without overwhelming the computer with data. The previous solution was to use a hierarchy of models, ranging from fine detail for tank battles to coarse mapping

for ICBM targeting. However, this raised the problem of linking the different models in a credible interactive mode. Our solution in JANUS is a hierarchy of terrains, all part of the same model. The player has push-button selection of several resolution levels, with a small grid size limited to the area of the tank battle.

Another problem that has plagued previous models is the aggregation and disaggregation of units—how to account for attrition during a battle and for the linking of two under-strength units into one. It is almost impossible (because of memory constraints) to use a computer to follow the detailed history of each tank and artillery piece in an army throughout a prolonged battle. However, when these weapons systems are traveling, resting, or waiting, they have no essential impact on the overall outcome. It is only when they are actually engaged in combat that they must be followed.

Therefore, in JANUS, all the tanks in a battalion move together in a specified formation until they are engaged. At that point, the unit separates into its subunits, and the results of the conflict are assessed. When the battle is over, the surviving subunits regroup and may be combined with other units, freeing additional computer memory.

The third area of improvement in JANUS is in the hierarchy of command. A captain's or a major's view of a battle is very different from that of a general. Thus, different views should be (and are, in JANUS) provided, with work stations of different scope and resolution—the fine detail for the lower command echelons and the broad view for the high command. We are experimenting with personal-size microcomputers for the latter stations.

Our development of JANUS has attracted wide interest from both the Army and the Air Force. The Army Training and Doctrine Command recently assigned two officers permanently to participate in further development. The potential applications range from officer training to evaluation of the war plans of forces stationed in Europe.

Furthermore, data taken in the course of these experiments confirm the scaling relationship from earlier experiments and increase confidence in our ability to predict conditions in laser-driven target implosions. However, the most important result of these experiments is that this confirmation of scaling allows us to predict with considerable confidence that targets irradiated at full Nova energies in green or ultraviolet light will achieve the thermonuclear-ignition threshold and possibly attain the scientific break-even point.

Other significant accomplishments in 1980 include:

- Demonstration that we can use flash x rays to photograph the imploding targets.

- Demonstration that we can obtain shock compressions to 5 TPa in gold targets by laser irradiation (potentially valuable in equation-of-state studies).³

- Achievement of essentially equivalent performance by optimization of the design of ICF targets for both heavy ion and laser drivers.

- Demonstration of target-sphere coating techniques involving molecular beams and electrostatic levitators, potentially capable of mass producing target spheres.⁵

- Production of target-quality glass shells coated with layers of metal and polymer and stepped plastic hemishells for double-shell targets.

- Fabrication of fuel-filled glass target spheres containing about 1% of bromine, with which we can make direct measurements of fuel compression.

- Successful cooling of fully assembled double-shell targets loaded with D-T fuel to the temperature of liquid helium.

- Demonstration that we can make optical components with graded refractive indices that will exceed the damage-resistance needed for surviving 200- to 300-kJ pulses of infrared, green, or ultraviolet light from the Nova laser system.³

- Completion of prototypes of most of the Nova hardware, including final packaging of the basic short-pulse oscillator.¹

- Development of plastic debris shields for Nova that distort the transmitted light

Targets irradiated at full Nova energies in green or ultraviolet light . . . will . . . achieve the thermonuclear-ignition threshold.

wavefront by less than 1/4 wavelength.¹

- Demonstration of a Raman-Stokes pulse compressor that concentrates 70% of the energy of a long pulse of light from a krypton fluoride laser into a very short pulse appropriate for driving the implosion of a fusion target.

- Completion of fluid-dynamic and full-system stress analyses of HYLIFE, our liquid-lithium-lined reactor-chamber concept for electric-power generation.⁶

Special Isotope Separation

The Office of Nuclear Materials Production is funding a special isotope separation program to investigate an array of laser techniques for isotope separation of special nuclear materials. Two elements, plutonium and tritium, are currently under investigation as candidates for laser-induced isotope separation processes.

Defense Projects (DOD)

LLNL conducts a variety of projects for the Department of Defense. The explosives, hydrodynamics, and warhead engineering capabilities we have developed for the nuclear explosives program place us in a unique position to help the DOD improve the performance of nonnuclear weapons systems. Also, our fusion energy research has given us facilities and expertise in generating charged particle beams, which someday may have military applications.

Nonnuclear Ordnance

Under the auspices of the Joint Cruise Missile Project Office of the Department of Defense, we are currently developing the VAM-93, a miniature bomb designed

Fig. 7

Artist's conception of a cruise missile attack on an airfield with VAM-93 cratering munitions. As the missile flies along the airstrip, it ejects groups of warheads at intervals. They descend by parachute and detonate on impact. Each warhead consists of a shaped charge that punches a small hole in the concrete, a velocity augmentor that drives the main part of the warhead under the concrete, and the main charge (insensitive high explosive), which achieves maximum upheaval damage by detonating only after it has penetrated the concrete.

The VAM-93 is a miniature bomb designed to break up Warsaw-Pact airfield runways in the event of a Soviet attack in Central Europe.

to break up Warsaw-Pact airfield runways in the event of a Soviet attack in Central Europe. One medium-range air-to-surface missile could carry a great many of these warheads and distribute them along a runway in a single low-level pass (Fig. 7). The VAM-93 warhead is 35 cm long, descends by parachute, and has three stages that function separately:

- A shaped charge in front that blows a small hole in the runway concrete, clearing the way for the main charge.
- A velocity augmentor that drives the main charge under the concrete for optimum performance.
- A main charge canister loaded with the explosive TATB that survives impact and detonates only after it has penetrated the runway, causing severe upheaval damage.

We have successfully fired the three stages of this warhead, singly and in combinations, in both static and dynamic tests.

Our current design efforts include studies to improve the performance of the

forward shaped charge, to reduce the case weight, and to increase the explosive energy of the main charge. We plan to test an optimized version of the VAM-93 this fall in live drops from a T-33 aircraft against a simulated runway section.

The successful performance of the VAM-93 has stimulated design studies of three larger versions: the VAM-114 and the VAM-125 for delivery by either a cruise missile or an aircraft and the VAM-165 for use as a hand-emplaced cratering munition.

Since October 1979, we have been engaged in a program for the Ballistic Missile Defense Advanced Technology Center to develop a three-dimensional Eulerian hydrocode (JOY) that can model hypervelocity impacts of shrapnel-like material on incoming ballistic missiles.

To fulfill its mission, the JOY computer code must be able to deal with strength-of-materials questions and the shock initiation of high explosives. It must also incorporate a method of transferring information to the structural-analysis code DYNA3D. We intend to use JOY to model the initial phases of impact (where stress levels are high and material motion is complicated) and then to let DYNA3D handle the much slower structural response. Most of the algorithms used in

JOY are based on techniques that have been well tested over several years.

A valuable extension of this work was a series of two-dimensional impact calculations embodying the first significant use at LLNL of elastic-plastic flow modeling in an Eulerian format. The successful completion of these calculations greatly improved our modeling capability.

The JOY code uses a Cartesian coordinate system within which grid planes can be programmed to move to perform an internal rezoning. It is a multifluid code with no fundamental limit on the number of regions that can be carried. It has second-order accuracy in the advection of mass, energy, and momentum. The standard analytic equation-of-state forms are all available.

JOY contains a variable-yield strength-of-materials model that treats work-hardening, pressure-hardening, thermal softening, and melting. Material failure models include both tensile and ductile failure. JOY also includes a proven HE shock-initiation model, and it possesses a versatile mesh generator capable of building three-dimensional figures from arbitrary planes, spheres, and conic sections. However, the graphics capability is still minimal.

JOY was written in a format consistent with standard FORTRAN usage so that it might be used on computers elsewhere. Within this portability constraint, however, it was designed for maximum efficiency on the Cray computer, making heavy use of the Cray's automatic vectorization capability and its ability to handle short vectors efficiently.

The speed of the code is quite problem-dependent. Observed speeds range from 25 to 70 μ s/zone cycle for pure hydrodynamic modeling and from 30 to 90 μ s/zone cycle when the elastic-plastic model is active. At the outset, we thought that computational speed would be the crucial consideration. Instead, we have found that the three-dimensional modeling capability is limited by the finite capacity of the computers and the resulting zoning constraints.

In October 1980, following a long shakedown period during which we checked out the code, added production features, and designed the link to

JOY can model hypervelocity impacts of shrapnel-like material on incoming ballistic missiles.

Fig. 8

Possible applications of charged-particle-beam accelerators, plotted in terms of the required beam energy and charge per pulse (current times pulse length). The Experimental Test Accelerator (ETA) and the Advanced Test Accelerator (ATA) occupy strategic locations where the requirements of several scientific and technological applications overlap.

DYNA3D, the code was put to work on simple impact studies. By the end of the year, JOY was making a substantial contribution to our programmatic studies.

Charged-Particle-Beam Research

Since June 1979, we have been operating an experimental test accelerator (ETA) based on the linear-magnetic-induction principle and incorporating other equipment and techniques developed for our Astron program.⁷ This accelerator delivers 30-ns 10-kA pulses of 5-MeV electrons, with up to five pulses in a burst and an interval between pulses as short as 1 ms. It has served as a technology test bed for the design of a larger version, the Advanced Test Accelerator (ATA), which will be capable of producing 50-MeV beams at the same currents and pulse rates. ATA construction is funded by the Defense Advanced Research Projects Agency (DARPA), with the Naval Surface Weapons Center as direct agent.

The ATA will be used to study the propagation of intense electron beams in air and the interactions of such beams with various materials. The potential military applications of such phenomena (in missile defense, for example) are of great interest (Fig. 8).

The essential difference between the ETA and the ATA is in the number of accelerator modules (10 for ETA; 195 for ATA), each of which increases the beam energy by 0.25 MeV. The added complexity of the ATA places great demands on hardware reliability and lifetime. The added length also makes accelerator instabilities more important and focusing requirements far more stringent.

Summary

During the past year, the emphasis in the nuclear weapons program has been on the development of new weapons, with planning toward a more vigorous experimental advanced development program next year. Our testing group has continued to develop and incorporate new instruments and techniques to expedite the measurement of significant explosion phenomena. We have done engineering design work on various warheads and have brought several to the production phase. In addition we have developed and applied JANUS, a greatly improved two-sided interactive combat-simulation code suitable for use in officer training and in evaluations of the war plans of forces stationed in Europe.

Inertial confinement fusion is even now useful for some kinds of weapons

research, and its usefulness will grow as we increase the output of energy of tiny D-T targets imploded by our large lasers. The Nova laser system, scheduled to be completed in the mid-1980s, is expected to demonstrate thermonuclear ignition and may also demonstrate energy break-even conditions.

During the past year, nonnuclear ordnance work has included the development of a three-dimensional hydrocode (JOY) that models hypervelocity impacts of shrapnel-like material on incoming ballistic missiles and the development of the VAM-93, a miniature bomb designed to break up airfield runways.

Construction of an Advanced Test Accelerator (ATA) is continuing. The ATA will be used to study the propagation of intense electron beams in air and the interactions of such beams with various materials. The potential military applications of such phenomena are of great interest. □

Key Words: Advanced Test Accelerator; beam weapons; Experimental Test Accelerator; Computer-Aided Design and Drafting; Drone; DYNA3D; gaseous tracers; ICF; inertial confinement fusion; JANUS; JOY; laser fusion; Nova laser system; seismic-reflection mapping; Shiva laser system; VAM-93; VAM-114; VAM-165.

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Energy and the

LLNL is applying its unique experience and capabilities to a variety of projects that will help the nation meet its energy needs in an environmentally acceptable manner.

LLNL projects aimed at helping the nation meet its energy needs go hand in hand with research into the sources of energy-related pollutants and their effects on plants, animals, and humans. The largest of the energy projects is our magnetic fusion energy program, with its long-range goal of developing the technology for a fusion power plant. Our atomic vapor laser isotope separation (AVLIS) program aims to demonstrate more efficient, more flexible, and less costly means of producing enriched uranium for nuclear energy. Also significant is the aluminum-air battery development (part of our transportation systems research program), which holds out the promise of an electric automotive propulsion system that would be independent of petroleum fuels and would provide a vehicle with performance comparable to that of today's automobiles.

Studies of the sources, methods of transport, and effects of energy-related pollutants (both nuclear and nonnuclear) are progressing under the direction of our biomedical and environmental research program, and we are participating in several Nuclear Regulatory Commission projects, including two foreign reactor-safety studies.

Energy

With the increasing awareness that fossil energy sources are finite, there is heightened interest in the development of alternatives. Several LLNL programs are making significant contributions in this area. Our magnetic fusion energy (MFE) program, which seeks to harness the

almost limitless energy of thermonuclear fusion, completed its tandem mirror experiment (TMX) last year, realizing a major breakthrough in magnetic confinement of fusion plasmas. Within the last year, our primary technology for laser isotope separation has been brought to the development stage where we can move into a major engineering effort to develop equipment that can be utilized in a production environment. Our aluminum-air battery program demonstrated both that the very promising electrochemistry of small test cells is definitely amenable to scale-up and that the cell stack and crystallizer work together as expected. Progress in these three programs is described below.

Magnetic Fusion Energy

Thermonuclear fusion, the process by which two light nuclei combine into one at extremely high temperatures (releasing energy as they do), is in many ways an ideal solution to the energy problem. Successful development of a fusion reactor would give us practical access to fuels—deuterium (from water) and lithium—that will last for millennia.

However, producing and controlling fusion reactions is difficult. They occur only at hundred-million-degree temperatures (as in the sun or in a hydrogen bomb). To produce such temperatures in a power plant and contain the fuel long enough to extract useful energy is beyond the capability of existing technology.

One possible solution to the problem is to rely upon specially shaped magnetic fields to confine the fuel (hot, ionized

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Fig. 1

A simplified cutaway drawing of our tandem mirror experiment (TMX). The TMX apparatus consists of a series of circular magnets (solenoid coils) in the central region capped at both ends by minimum-B (baseball) magnets. We use plasma guns at the end of the machine to create a plasma initially. Then, to heat the plasma, we inject energetic beams of deuterium atoms (neutral beams) from outside. The solenoid section provides a large reservoir of heated ions, and the minimum-B magnets provide an electrostatic barrier that keeps the ions from leaking out the ends. The entire apparatus is enclosed in a vacuum vessel, which excludes contaminating gas molecules that would cool the plasma. The auxiliary plasma-shaping coils (C-coils, transition coils, and octupole coils) make a smooth transition between the central magnetic field and the end-cell fields. The minimum-B magnets are turned so as to orient the fan-shaped ends of the plasma flux tube at right angles to each other, enhancing confinement.

gases known as plasmas), while heating it to fusion temperatures by some external means. This approach is followed by our MFE program.¹⁻³ Another approach, inertial confinement fusion, is described on p. 12 of this issue.

Magnetic fusion development has not yet reached the point where we can specify the exact form of a fusion power plant, but recently we have made great strides toward that goal.

During 1980, the MFE program's Tandem Mirror Experiment¹ completed a three-phase experimental program begun in late 1978. After an eight-month checkout period and a six-month initial operating period, it advanced into a ten-month experimental phase in which we corroborated the initial results and carried out many detailed physics investigations. These experiments confirmed our expectations based on theory; the tandem mirror device, with minimum-B magnetic fields plugging the ends of a straight solenoid field (Fig. 1), confines the hot plasma better than any of our previous machines.

The TMX experiments verified that we could sustain density gradients within the plasma by means of neutral-beam injection and that the resulting electrostatic potential gradients turn back ions that would otherwise escape from the central

cell. As a result, the TMX end plugs improved confinement of the central-cell plasma by as much as a factor of nine.

We also measured the central-cell plasma potential as a function of radius and showed that the confining electrostatic potential gradient is not localized near the axis but extends over a radius of 25 cm. Radial and axial profile measurements of plasma density and temperature confirm the large volume of plasma confined in the central cell. We also generated and maintained end-plug potentials exceeding 1 kV.

The TMX design provided a hundred-fold improvement in electron-energy confinement. This came about because the end-plug plasmas were stabilized by low-energy plasma from the central cell. The result was an effective decoupling of the plasma from the end walls. Thus, end-plug electron temperatures of 20 eV were achieved (three to four times higher than levels reached in the past with comparable neutral-beam power). The cool end-wall plasmas had a very low density (ten thousand times lower than that in the end plug). This decoupling will be an essential feature of future high-temperature MFE machines.

Another significant accomplishment was a remarkably low central-cell

Fig. 2

The upgraded TMX machine, which features a thermal barrier in the end cells and oblique injection of neutral beams in the central cell (45° to the axis rather than 90°). The thermal barrier serves to isolate the end-cell electrons from those in the central cell and permit them to be heated by tuned microwave energy (electron-cyclotron-resonance heating, or ECRH). This, in turn, expedites their escape from the plasma, raising the local plasma potential beyond what would be possible with density gradients alone. Oblique neutral-beam injection is expected to improve the microstability of the end-cell plasmas. The size of the men in the foreground indicates the size of the machine.

impurity level (0.5%), which kept the power loss due to impurity radiation to less than 10%. High-resolution spectroscopy of the impurity radiation and diamagnetic-loop measurements indicate central-cell ion temperatures of 100 to 200 eV.

The TMX diagnostic instruments^{1,4} provided large quantities of data over a broad spectrum of operating conditions. Comparisons between this body of data and theoretical predictions already has resulted in improved computer models for describing plasma performance over a wide range of input parameters.⁵ We are also developing better tools for analyzing novel magnetic configurations for plasma-confinement stability.

The breakthrough in plasma-containment characteristics demonstrated in the TMX justified a complete revision of our magnetic fusion energy development timetable. We immediately redesigned the Mirror-Fusion Test Facility (MFTF), already 85% finished and originally scheduled for completion in 1981, converting it from a single-mirror to

a tandem-mirror configuration (MFTF-B).² When it goes into operation in 1985, the MFTF-B may be capable of demonstrating with deuterium alone that power-break-even plasma conditions would be achieved if deuterium and tritium were both used (as they would be in an actual reactor). We also designed and began construction of an upgraded TMX (Fig. 2), to be completed in the fall of 1981.

The system for maintaining plasma-potential barriers that was successful in the TMX (neutral-beam injection) would, if enlarged to the size needed for a power-producing reactor, require central magnetic fields of 17 T and neutral-beam injection approaching 1 MeV. It would be difficult to meet these requirements, even with advanced technology now in development. We are, therefore, investigating alternative end-plug configurations that will operate within more modest limits.

One of these alternatives is the thermal-barrier concept, which would isolate the end-plug electrons and make it possible to

Successful development of a fusion reactor would give us practical access to fuels—deuterium (from water) and lithium—that will last for millenia.

use microwaves to heat them independently. This would produce the necessary end-plug potential gradient without such a large density gradient, reducing the magnetic field and neutral-beam-energy requirements. We will be testing this concept in the TMX Upgrade, together with a new 45° neutral-beam injection angle, which should improve the microstability of the end-plug plasma confinement. We are also planning to apply these concepts in the MFTF-B machine.

The MFTF-B will be much larger and more powerful than the TMX. Whereas the TMX operated in 25-ms pulses and used water-cooled magnets, the MFTF-B will use superconducting magnets (shown on p. 26) and 30-s neutral beams. Figure 3 indicates the scale of this equipment and some of the details of construction.

Nearly all the equipment purchased or constructed for the MFTF will be used in the MFTF-B. This includes the 230-kV, 250-MW pulsed power subsystem, the twenty-four 80-kV, 88-A dc power subsystems of the sustaining neutral-beam-injector power supplies, the 10.6-m-diam vacuum vessel, the cryogenic system for liquefying, distributing, and recovering helium, and the superconducting yin-yang magnets.

The MFTF-B will use a unique, completely computerized control and diagnostic system that provides a hierarchical structure for the collection, communication, processing, and display of information. Much of this equipment has already been delivered and tested.

The magnetic fusion energy program is making good progress toward its goals. The MFTF-B machine, scheduled for operation in 1985, approaches the size and complexity of a fusion reactor and is expected to demonstrate break-even plasma conditions over relatively long periods (30 s).

Laser Isotope Separation

The Department of Energy, Office of Nuclear Energy, sponsors three advanced isotope separation programs with the goal of demonstrating more efficient, flexible, and less costly enrichment of uranium for nuclear reactor fuel. We expect a decision within the next year as to which advanced isotope separation technology will be

Fig. 3

The MFTF-B tandem mirror machine, now under construction. The end-cell magnets in this machine form a thermal barrier similar to that in the upgraded TMX but differently placed and with different implications for plasma stability. MFTF-B uses superconducting magnets, enabling it to generate higher magnetic fields and to sustain them indefinitely. Neutral-beam pulse lengths up to 30 s are planned.

carried through full-scale engineering demonstration in the later 1980s.

The advanced isotope separation program for uranium at LLNL has the objective of developing the atomic vapor laser isotope separation (AVLIS) process, which promises a significant reduction in plant capital costs over other isotope separation processes, as well as reduced power requirements and operating costs.

LLNL's primary laser isotope separation technology uses copper-vapor pumped dye-lasers to selectively ionize atomic vapor by means of powerful, tunable, laser radiation. The resulting ions are separated from the neutral-vapor stream and collected as enriched product. In the last year, we have brought this technology to the point where we can move into a major engineering effort to develop production equipment.

Existing integrated research facilities for lasers and vaporizers, developed and operated over the past several years, will continue to operate and provide further refinement and improvement in our basic understanding of this important new process technology.

The Aluminum-Air Battery for Electric Vehicles

One way of supplying the long-term energy needs of highway vehicles and of overcoming the balance-of-payments problem posed by excessive oil imports is to develop energy-storage propulsion systems that draw upon electricity produced from nonpetroleum fuels. Electrically rechargeable batteries may someday power short-range electric vehicles for specialty markets. However, if we are to build a competitive, general-purpose electric vehicle, we must look beyond conventional batteries to such concepts as that of the aluminum-air battery.⁶

LLNL is the lead laboratory for DOE development of metal-air batteries. The aluminum-air battery is one of the key elements in that program. It is expected to provide an electric vehicle with the range, acceleration, and rapid-refueling capability of today's automobiles. Our role is to provide technical direction for the project and to conduct research in certain areas critical to the integration of the diverse technologies involved. Much of the development work is carried out by industrial subcontractors with unique expertise in certain problem areas.

Fig. 4

Diagram of a complete aluminum-air battery system. Electrolyte is circulated between the cell stack and the crystallizer where the hydrargillite reaction product can be crystallized. The hydrargillite is then washed, partially drained, and stored. (When removed from the system, it will be recycled to produce more aluminum and possibly aluminum fuel plates.) Air enters the system, is scrubbed to remove carbon dioxide and road dirt, saturated with water, and, finally, reacted in the cell stack. Water is condensed from the exiting air, which is then vented to the atmosphere. The condenser supplies distilled water for washing the hydrargillite, and that water subsequently enters the crystallizer where it becomes a reactant. Circulating tap water also transfers heat from the electrolyte to the atmosphere and heats the incoming air.

The overall aluminum-air battery system for a private highway vehicle is diagrammed in Fig. 4. In addition to the cell stack and crystallizer, components are provided to remove carbon dioxide and road dirt from the incoming air stream and to wash, drain, and store the hydrargillite (the end product of the reaction in the aluminum-air battery). Tap water is evaporated into the incoming air, and a portion is then condensed from the exhaust of the cell stack to provide for the chemical reaction and to remove soluble caustic impurities from the hydrargillite. The battery is recharged by the addition of tap water (every 400 km, or 250 mi) and fresh aluminum plates (at intervals of 1600 to 2800 km, or 1000 to 3000 mi).

We recently finished testing a number of 25- to 50-cm² (4- to 8-in.²) single power cells. The normal operating voltage of these cells (1.55 V at 2 kA/m²) is 30% greater than that achieved at the start of the battery development program, and the peak power of 6.3 kW/m² is twice that originally projected for an aluminum-air power cell. This year, we also tested full-size 1000-cm² (1.1-ft²) cells with full-scale crystallizer units (used to control the electrolyte concentration in the cells and to produce metallurgical-grade

hydrargillite). Our results indicate that the voltage per unit electrode area in the larger cells does not differ significantly from that achieved with the small cells. While technical problems must yet be solved in the development of a rapidly refuelable 1000-cm² cell, the electrochemistry appears to be amenable to scale-up.

We currently are testing rapidly refuelable cells and shortly will begin testing multicell stacks. Our plans call for the demonstration of a rapidly refuelable, 40- to 60-kW, 70- to 100-kWh laboratory prototype in 1985 and of a battery suitable for installation in a vehicle by 1987.

There are difficult problems that must be resolved before we can fully establish the technical and economic viability of the aluminum-air battery. However, successful development of the battery would make it possible to build an electric vehicle competitive in performance and cost with internal combustion vehicles powered by synthetic liquid fuels derived from coal.

Environment

Unique LLNL experience and capabilities contribute to investigations of a variety of environmental and biomedical

problems. We have developed techniques for use in studies of the effects on human cells of pollutants in the environment—for example, the production of cancer-related gene mutations. We are analyzing environmental impact and required control technologies in connection with future geothermal development in California's Imperial Valley. We are also evaluating the feasibility of safe and reliable short-term storage of spent commercial-reactor-fuel assemblies at a realistic repository depth in common granite rock in Nevada. Our Atmospheric Release Advisory Capability (ARAC) has enabled us to provide accurate and timely information about the probable effects of atmospheric release of radioactive and other toxic materials. Below, we describe briefly work that is representative of LLNL's efforts in these areas.

Biomedical Sciences

The major emphasis in our biomedical program is on studies of genetic injury and cancer-related biology in humans. We continue to emphasize flow cytometry, a powerful new way to analyze and separate cells at high speed and resolution. In the past year, we have learned how to prepare human blood samples for chromosome analysis by flow cytometry; now, we can resolve 20 of the 24 human chromosomes automatically and routinely. This year, working with scientists at the University of California at San Francisco (UCSF), we used chromosomal sorting done with flow cytometry to determine that the gene for producing insulin is located on the short arm of the human chromosome 11.

We are also using flow cytometry for a human somatic mutation assay to detect the rare (one in 10 million) red blood cells that contain mutant sickle hemoglobin. This year, we initiated a small clinical trial to compare the incidence of sickle hemoglobin in normal individuals with that of patients undergoing cancer chemotherapy.

The feasibility of using flow cytometry for automated cancer screening of Pap-test specimens is now accepted, and the approach is being evaluated in a series of pilot studies. In the first of these studies, specimens obtained from 74 women who were clinic patients at UCSF were

With flow cytometry, we can resolve 20 of the 24 human chromosomes automatically and routinely.

screened for abnormal (dysplastic and cancerous) and normal cervical specimens. The flow cytometry method yielded less than 10% false negative and 32% false positive reports. We hope to reduce the proportion of false positives in a larger study now under way that uses specimens from a group of normal non-hospitalized women, LLNL volunteers.

We are continuing to evaluate abnormal sperm morphology in man as an important indicator of genetic damage. Two approaches that show great promise are flow cytometry using slit illumination and image analysis using scanning microscopy. In addition, this year we significantly improved a test that estimates the number of Y chromosomes per human sperm.

Studies of sister chromatid exchange in blood cells of LLNL employees were begun this year with the objective of identifying and quantifying personal factors that might affect results of this important genetic assay. A clear dose-related effect of cigarette smoking has already been found. Meanwhile, laboratory studies are making rapid progress in determining the mechanism and significance of sister chromatid exchange.

Recently, we initiated a restudy of the health-effects data from Hiroshima and Nagasaki in the light of dosimetry calculations done by LLNL under weapons program sponsorship (see p. 9). These new calculations indicate that the gamma-ray component and total dose were lower in Nagasaki and substantially higher in Hiroshima than previously believed, while the neutron component was much lower

in both cities. The data accumulated by the Atomic Bomb Casualty Commission and its successor, the Radiation Effects Research Foundation, are being reevaluated to determine the effect of the new dose calculations on values for the relative biological effectiveness of neutrons and on the risk coefficients of radiation-induced cancer and chromosome damage, and the consequences for radiation protection.

Environmental Sciences

A significant fraction of our environmental effort in the past few years has been devoted to assessment of the impact of geothermal resource development. These activities are nearing completion. We designed a computer model to identify the land-use constraints and conflicts posed by geothermal resource development in The Geysers region of California. This model can be used to evaluate sites, areas, or regions for geothermal development or for any land-intensive energy development. Our detailed analysis of the environmental impact and control technologies associated with future geothermal development in California's Imperial Valley provides necessary information for developing this resource in an environmentally sound manner.

A major phase of our continuing activities in assessing the radiological condition of the Marshall Islands ended this year as we completed a study of the radiological consequences of resettling Bikini and Eniwetok Atolls. This study will provide a basis for recommended resettlement scenarios that minimize radiological consequences.

Our projects relating to environmental protection require instrumentation that meets very stringent requirements. For example, many of our field studies require instruments that are portable, durable, respond rapidly, and have high sensitivity and discrimination. This year, we designed and tested a portable rapid-response sensor for measuring the concentration of methane and ethane in the dense fogs produced by liquefied natural gas spills on water. Several of these sensors have been built for use in the LLNL Liquefied Energy Fuels dispersion tests at China Lake, California.

Deep Geologic Storage of Spent Reactor Fuel

The objective of LLNL's spent-fuel test in the Climax granite at the Nevada Test Site is to evaluate the feasibility of safe and reliable short-term storage of spent commercial-reactor-fuel assemblies at a plausible repository depth in common granite, followed by retrieval of the fuel. During this five-year project, we will collect data needed to evaluate granite as a medium for deep geologic disposal of highly radioactive reactor waste and to design such a repository in granite.

Using existing mining, engineering, and electronics technologies, we have constructed one storage drift of a hypothetical repository at the Nevada Test Site, 420 m below the surface in the Climax granite stock. By imposing appropriate boundary conditions, we subject the encased spent-fuel assemblies and the surrounding rock mass to the thermo-mechanical and radiation effects that would occur in a large-scale repository. We are also comparing *in situ* the effects on granite of heat alone (electrical heaters) with the effects of high-level ionizing radiation plus heat (spent fuel). We use an extensive array of instrumentation deployed at more than 600 locations to monitor the temperatures, radiation levels, stresses, and displacements occurring in the test facility.

During April and May of 1980, 11 canisters of spent fuel approximately 2.5 years out of the reactor core and 6 electrically heated simulators were emplaced in the test storage drift. Monitoring of the temperatures of the spent-fuel canisters, the steel hole liners, and the surrounding rock revealed that peak canister temperatures of about 145°C were reached in late July and early August of 1980. The fuel canisters and hole liners are now cooling gradually, while the surrounding rock is still heating slowly. To demonstrate the feasibility of retrieving the spent-fuel assemblies from storage, we made a successful exchange of one of the spent-fuel canisters in January 1981.

Because this spent-fuel test site is the only facility in the world where high-level reactor waste is in deep geologic storage, the test has received much public attention. Emplacement of the first spent-fuel

Table 1 Summary of ARAC responses during FY-1980.

Date	Type of Response	Problem	Location	Duration
1979				
Oct. 2	Alert	Reactor leak	Red Wing, Minn. sota	2.5 h
Nov. 26-28	Exercise	Stimulated weapon accident	Fort Ord, California	3 d
1980				
Jan. 24	Alert	Earthquake	LLNL, California	3 h
Feb. 26	Exercise	Nuclear spill	LLNL, California	6 h
Feb. 26	Alert	Reactor spill	Crystal River, Florida	3 h
Apr. 17	Alert	Plutonium glove-box incident	LLNL, California	2 h
May 21-28	Incident	Hydrogen sulfide leak	Savannah River Plant, South Carolina	8 d
June 15-27	Exercise	Release tests	Three Mile Island, Pennsylvania	12 d
June 21-27	Exercise	Simulated nuclear extortion	NEST-80	6 d
June 28-July 11	Incident	Krypton-85 purge	Three Mile Island, Pennsylvania	13 d
July 3	Alert	Radioactive-waste filter fire	Rocky Flats Plant, Colorado	2 h
Sept. 9	Exercise	State-coordinated exercise	Rocky Flats Plant, Colorado	6 h
Sept. 19	Incident	Titan II missile accident	Damascus, Arkansas	12 h

canisters was given full media coverage, and since then we have conducted more than 120 tours for approximately 1600 representatives of technical, government, and public interest groups from the U.S. and 22 foreign countries. To disseminate our engineering and scientific findings, we have published and presented 26 technical papers.

In the first year of this five-year test, we have demonstrated that spent fuel from commercial reactors can be safely and reliably encapsulated, transported, placed into, and retrieved from deep geologic media using current technologies. We have confirmed that granite can accommodate the thermal and mechanical loads imposed by a repository, exhibiting only small deformations that produce no apparent hazard to structural stability. In addition, we have found that existing thermal computer models adequately predict the response of the rock mass to the imposed loads; however, the mechanical and thermomechanical models are not adequate and must be improved.

Recent ARAC Activities

Since responding to the Three Mile Island accident in 1979, LLNL's At-

mospheric Release Advisory Capability (ARAC) has provided its services in a number of other incidents, exercises, and alerts (Table 1). In 1980, two of these incidents occurred with no advance notice. On the morning of May 21, 1980, a cracked pipe in a storage tank at the Savannah River Plant released a small quantity of toxic hydrogen sulfide gas. Because the total amount of gas stored in the tank posed a potential hazard, local officials suspended highway, rail, and river traffic in the area while plant engineers sought to contain the danger. As an additional precautionary measure, ARAC support at the Savannah River Plant site was requested.

At the Plant, staff members prepared real-time calculations of likely plume-transport routes and diffusion rates in the event of an external release of the gas. Then, as the threat stabilized, they estimated probable drainage flow and associated plume-transport routes under nighttime meteorological conditions to anticipate the most likely zones of public risk; Fig. 5 shows a calculated isopleth pattern for the hydrogen sulfide gas. Fortunately, it proved possible to eliminate the hazard by means of an engineering

Fig. 5

Isopleth pattern of the instantaneous atmospheric concentration of hydrogen sulfide gas 2 m above ground level near the Savannah River Plant, calculated for 3 h after commencement of a simulated continuous leak. The isopleths are in units of ppm (parts of gas per million parts of air) ranging from 1 to 1000.

solution. The ARAC staff provided support throughout the eight-day duration of the incident.

ARAC's second response to an incident with no advance notice was on September 19, 1980, when a Titan II missile silo accident near Damascus, Arkansas, presented the possibility of a release of radioactive material. Our task in this case, using newly developed capabilities, was to compile essential files on local topography, meteorological stations, and geography. We also generated a series of alternative scenarios to bracket the potential hazard.

A third incident, in which ARAC's participation was planned, was the purging of radioactive krypton-85 gas from the Unit 2 reactor-containment building at Three Mile Island. Our participation in this event was extensive. ARAC's primary role was to provide an independent assess-

ment system to support the Environmental Protection Agency and the State of Pennsylvania during the planned release. For two weeks preceding the purge, we conducted numerous tests and exercises; subsequently, twelve 24-h days were spent in supporting the calculation and data-collection efforts. Helicopters and mobile measurement systems were deployed to confirm our calculations.

As a result of ARAC's successful participation in the Three Mile Island operations and the two incidents for which there was no advance notice, plans are now being formulated to expand the scale of its activities. Round-the-clock emergency services will soon be available to agencies of Federal, state, and local government in accidents entailing the potential or actual release of radioactive materials to the atmosphere.

Nuclear Regulatory Commission Projects

As the number of nuclear power plants around the world has increased, there has been growing concern about the safety of reactors. In support of the Nuclear Regulatory Commission (NRC), scientists at LLNL are providing technical assistance in reactor safety by studying such diverse factors as earthquakes, engineering problems, and human behavior as they affect the operation of nuclear power plants, and by evaluating various provisions for safeguarding special nuclear material.

Recently, LLNL completed extensive tests and analyses to define the air-transient loading on parts of a boiling-water-reactor pressure containment system. These loads, which result from fluid forces caused by a pipe break (i.e., a loss-of-coolant accident), were studied using our one-fifth-scale MARK I Pressure Suppression Experiment. After this work was completed, the Nuclear Regulatory Commission decided to make use of information from foreign reactor-safety research programs, and LLNL was designated as the principal liaison to these programs.

Because earlier investigations have revealed that significant theoretical difficulties are encountered when reduced-scale steam test data are applied to full-scale plants, our liaison efforts are focused on the full-scale containment research programs at the GKSS Forschungszentrum Geestacht GmbH, West Germany (GKSS-PSS program), and at the Japan Atomic Energy Research Institute, Tokai-Mura (JAERI-CRT program).

It soon became clear that we could not provide satisfactory information for the NRC by simply reviewing test data reports. We have, therefore, adopted an approach wherein we (LLNL) are a responsible part of the research staff for each of these foreign programs. By visiting and working on these projects, consulting on the measurement systems, reviewing the raw data, and participating in the design of experiments, we are able not only to contribute to the research being done but also to improve the information flow to the NRC. This approach has been well received by the management

and staff of both programs so that we are in a very real sense engaged in two full-scale reactor-containment test programs, one in West Germany and one in Japan.

The primary purpose of our liaison with these two foreign programs is to develop an improved understanding of steam-condensation processes and to better define the associated load functions in the multivent pressure suppression system. To these ends, GKSS-PSS is providing us with subsets of their original data tapes. We have developed many computer programs, drawing on our earlier pressure suppression experiments, that enable us to exploit LLNL's advanced computing capabilities and perform extensive time- and frequency-domain analyses of the data.

We are also assisting in the design of the measurement systems used in both foreign programs to ensure that the data obtained are as accurate and as complete as possible. Because the pressure measurements are of particular importance, we at LLNL developed a technique for desensitizing pressure transducers to temperature transients (enabling them to be used in conditions with varying temperatures). This method has been extensively applied at the GKSS-PSS program and has yielded valuable data.

We have also assisted in the application of a rod lens (used in our earlier pressure suppression experiments) in the GKSS-PSS facility that permits viewing of the steam-condensation processes during each experiment. With the aid of this device, we expect to obtain data that will increase our understanding of the source of the highly dynamic and oscillatory loads that develop during a loss-of-coolant accident.

In the near future, we will use techniques developed at LLNL to measure the natural frequencies and mode shapes both before and after the walls of the JAERI-CRT test facility are stiffened. These measurements will provide useful information applicable to the response of a full-scale reactor facility to loads applied by fluid forces that occur in a loss-of-coolant accident.

Summary

LLNL's Tandem Mirror Experiment demonstrated a breakthrough in plasma

confinement last year that has justified a complete revision of our magnetic fusion energy development timetable. The MFTF-B machine, scheduled for operation in 1985, approaches the size and complexity of a fusion reactor and is expected to demonstrate break-even plasma conditions over relatively long periods of time (30 s).

In the last year, our laser isotope separation program has brought the primary technology for this important new process to the stage where a major engineering effort can be directed to the development of equipment to provide a production capability for special nuclear material.

We have tested a full-size aluminum-air power cell, demonstrating that the electrochemistry of small test cells is amenable to scale-up. We have also successfully tested the operation of the cell stack and crystallizer together. An experimental battery based on these results has potential as a power source for electric vehicles with the range, acceleration, and rapid-refueling capabilities of conventional automobiles.

The major emphasis in our biomedical program has been on studies of genetic injury and cancer-related biology in humans. A significant fraction of our environmental effort has been devoted to assessment of the impact of geothermal resource development.

In the first year of a five-year test, we have demonstrated that spent fuel from commercial reactors can be safely and reliably encapsulated, transported, placed into, and retrieved from deep geologic media using current technologies and have confirmed that granite rock can accommodate the thermal and mechanical loads imposed by a repository.

Since responding to the Three Mile Island accident in 1979, LLNL's Atmospheric Release Advisory Capability (ARAC) has provided its services in a number of other incidents, exercises, and alerts.

As part of our work for the Nuclear Regulatory Commission, we are monitoring reactor-safety experiments being conducted in Germany and Japan. □

Key words: air pollution; aluminum; ARAC; Atmospheric Release Advisory Capability; boiling water reactors; cells—analysis, effects of radiation; cytology—automation; electric batteries; electric vehicles; flow cytometry; geothermal development; instrumentation; land-use models; laser isotope separation; magnetic fusion energy; MFE; MFTF-B; Nevada Test Site, nuclear safety; radioactivity—measurements; reactor fuel; reactors—containment vessels, pressure suppression systems, safety; spent fuel; spent-fuel storage; toxic chemicals—measurements; TMX.

Spent fuel from commercial reactors can be safely and reliably encapsulated, transported, placed into, and retrieved from deep geologic storage using current technologies.

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Support Projects

A sampling of recent achievements by LLNL support organizations indicates their diversity, their technical sophistication, and their importance.

The research programs at LLNL (weapons, magnetic fusion energy, laser fusion, biomedical and environmental, and energy and resource programs) call upon various support organizations for

help in meeting their objectives. These support organizations, defined for the most part in terms of areas of technical specialization (such as chemistry, physics, engineering, and computation), are a

valuable asset to the Laboratory because they keep pace with developments in the various disciplines and provide pools of well-trained professionals capable of lending their expertise to the new and constantly changing technical problems faced in the major research programs.

The Laboratory's organizational structure can best be described as a matrix, in which individual personnel function not only under the direct and immediate supervision of a particular program but often under the general administrative umbrella of a support organization. For example, a group of engineers assigned to focus on the problems of inertial confinement fusion would function under the immediate supervision of the program itself while retaining membership in the broader engineering departments, to which they would look for general professional guidance and support (and for a new assignment when the immediate programmatic tasks are completed). Our matrix organization, one of the oldest in the country, was designed to allow the fullest and most effective use of employees' skills while affording great flexibility as programmatic needs change.

The Laboratory's support organizations carry on sophisticated theoretical and experimental projects, many of which have applications that serve not only LLNL programs but also the interests of the broader technical community. Thus, investigations into the tensile strength of a polymer fiber conducted by a support group in connection with a particular Laboratory program may also be of help to industries seeking a light and durable packaging material. A new instrument developed to measure irregularities on a polished optical surface that will be used as a laser target may provide engineers outside the Laboratory with a tool for refining other optical devices.

The six projects described in this article provide a sampling of the diverse support activities performed by the chemistry and materials science, computation, physics, and engineering departments at LLNL during the past year. They include work on the structure of Kevlar fibers, light propagation in optical fibers, mechanisms influencing gun-barrel erosion, structural models of the giant

planets, optical surface profilometry, and a unique computational facility for the magnetic fusion energy program.

Determining the Structure of Kevlar Fibers

Fiber/epoxy composites are being used to make strong, lightweight structural components that are expected to maintain their structural integrity for years. Graphite, glass, and boron fibers have been available for several decades, and their structures and mechanical properties are well known. However, fibers of poly(p-phenylene terephthalamide), or PPTA, which is manufactured by duPont as Kevlar, have been available only in the last decade. Thus, the properties of this material, especially its durability, have not been completely defined. Accurate prediction of fiber durability requires a detailed understanding of the physical structure of the fiber, how the structure relates to the deformation and failure mechanisms observed, and how this relationship is modified by the service environment. The LLNL Chemistry and Materials Science Department is investigating the relation of Kevlar structure to fiber deformation and failure.¹

The primary sponsors of this work have been the Nuclear Weapons Program, the Nonnuclear Ordnance Program, NASA, the European Space Agency, and the DOE Energy Conservation Division. The applications include flexible armor, pressure vessels, satellites, motor cases, aircraft components, flywheels, tankage, and surface transportation components, among others.

Kevlar fibers are formed by spinning filaments of warm PPTA-sulfuric acid solution into a cold-water coagulation bath. During cooling, the interior of the cylindrical PPTA-H₂SO₄ dope crystallizes, whereas the rapid cooling of the exterior results in a noncrystalline skin. Subsequent treatment of the solidified dope involves H₂O-H₂SO₄ exchange in the water coagulation bath, sodium hydroxide neutralization of the H₂SO₄, washing of the resultant H₂SO₄ with water, and drying of the fibers at 65°C. After drying, the fibers have a modulus of 65 GPa and are referred to as

Fig. 1

Scanning electron photomicrograph of the axially fractured surface of a Kevlar 49 fiber, revealing the presence of periodically occurring, internal transverse planes (red). These planes, formed when the PPTA-sulfuric acid solution is spun into the coagulation bath and crystallized, constitute an inherent weakness in the Kevlar fibers. There are no such planes in the outer skin (blue) of the fiber because its constituent molecular chains end at randomly distributed points.

Kevlar 29 fibers (used in automobile tires). Further heat treatment at 550°C under stress aligns the PPTA molecules more perfectly, doubling the fiber modulus to 125 GPa; this produces Kevlar 49 fibers.

Electron photomicrographs of Kevlar fibers reveal that the bulky, ionic end groups of the PPTA molecules cluster in planes upon crystallization (Fig. 1). These internal planes occur about every 200 nm (the average PPTA molecular length) along the fiber axis. However, in the non-crystalline skin, the bulky end groups are nearly randomly distributed. Thus, in the longitudinal fiber direction, the skin has more continuous structural integrity than does the crystalline fiber core.

We have found that Kevlar fibers, in the form of unimpregnated yarns and epoxy composites, fail under tension by splitting longitudinally 200 to 700 μm in the direction of the fiber length. After prolonged periods of stress, the fiber ages, and the fiber split length decreases as a result of macromolecular chain scission.

The fiber split lengths are predominantly controlled by the noncrystalline skin with its nearly random chain-end distribution. Therefore, any damage to this

skin (e.g., during fabrication of the composite or during composite deformation) will degrade the fiber strength. Our studies have indicated that a strong bond between the epoxy matrix and the Kevlar fiber in the composite is undesirable because such a bond may damage the fiber skin.

We have used transmission optical microscopy of Kevlar 49 fibers to study transverse defect planes in the fiber core occurring periodically along the fiber axis. As expected, these planes become more pronounced under tensile stress. We have observed two distinct deformation processes when Kevlar 49 fibers are stressed under tension. In the first, each internal defect plane deforms nearly equally, and the fiber skin deforms uniformly. In the second, certain defect planes deform considerably more than others, and a portion of the skin adjacent to one of these defect planes fractures and peels away from the fiber core. We believe that these skin-core deformation processes, which are consistent with our fiber model, involve both slipping and breaking of the PPTA molecular chains.

Further studies are being conducted to correlate PPTA fiber structure with fiber

strength. We are also monitoring the breakage of PPTA molecular chains under various service environments using electron spin resonance spectroscopy. These studies will enable us to describe the durability of the Kevlar fiber in terms of molecular structure and failure mechanisms.

Light Propagation in Optical Fibers

During the past decade there has been an explosive growth in the use of hair-thin glass fibers to carry information coded into pulses of light.² This rapid growth has been spurred by the many technical advantages offered by optical fibers, including their small size, low weight, immunity to electromagnetic interference, and high information-carrying capacity. Fiber-optics technology is being used in the telecommunications industry, in the planned MX missile complex, in the LLNL Shiva laser fusion experiment, and in nuclear experiments at the Nevada Test Site.

In support of Department of Energy (DOE) defense programs at LLNL (but with many different applications in mind), the LLNL Physics Department has developed over the past few years a very accurate and complete wave-optics description of light propagation in optical fibers. In any waveguide structure, the propagated light can be resolved into a number of normal modes (i.e., simple vibrations with an unchanging shape and rate that combine to form the total field, which is constantly changing). In the past, attempts have been made to calculate these individual modes directly. Our method, called the propagating beam method, differs from other approaches in that it determines the total, multiple-mode field. The individual modes may be recovered *a posteriori* through Fourier analysis of the transmitted field. That is, a kind of numerical spectroscopy allows the calculated field to be decomposed into its constituent modes.

We have checked the propagating beam method extensively for accuracy by comparing it with analytic solutions where they exist. Individual mode shapes, propagation constants, and modal group

velocities all show excellent agreement for those cases where comparisons could be made. This increases our confidence in applying the method in other cases. Our approach has been used to address a number of significant practical questions, including dispersion (the spreading of pulses over time, leading to a blurring of distinctions), signal attenuation, and the effect of splices.

The propagating beam method gives an accurate description of light propagation and dispersion in realistic optical fibers. It may be used to study other waveguide systems as well, as its recent application to optical resonators has shown. The method provides a powerful tool for understanding basic properties of waveguides and should lead to a variety of practical applications.

Mechanisms Influencing Gun-Barrel Erosion

Modern chemical propellants produce higher temperatures and pressures in the firing chamber of cannon than do conventional propellants.³ If the fit between the barrel and the projectile is correct, the higher pressure makes it possible to fire a projectile with increased momentum (i.e., either greater mass or higher muzzle velocity), thus increasing range and penetrating power. At the same time, the combination of high temperature and pressure results in increased heat transfer and stress, which may cause the gun barrels to wear out much faster than they do with the conventional propellants. The Physics Department has undertaken for the Department of the Army a three-year program of fundamental erosion-corrosion research to determine the processes affecting the erosion of large-caliber cannon barrels.

Using a 14-MPa pressure chamber, we are testing the influence of various combinations of combustion-gas components on selected materials subjected to elevated pressures and laser-heated to high temperatures. We expose a variety of high-temperature-resistant metals to inert gases such as argon, chemically active gases such as nitrogen, oxygen, and hydrogen, and gas mixtures such as air, carbon monoxide, and carbon dioxide. By

We have undertaken a three-year program of fundamental erosion-corrosion research . . . to determine the processes affecting the erosion of large-caliber cannon barrels.

chemical and metallurgical analysis of the effects of heat, pressure, and chemical reactions on the metals, we should find clues to the influence of both the erosive-corrosive aspects of the gas environment and the response and resistance of particular materials to the environments.

One way to minimize gun-barrel erosion, or at least reduce it, is to make the metal surface less reactive. For this reason, our experiments using steel that is coated with a refractory layer are very important. We coated steel targets with a thin layer of nickel to increase adherence. Over this, we deposited a thick layer of refractory tungsten for heat resistance. We discovered that the thicker the nickel layer, the longer the tungsten layer lasted and the longer the steel was protected. Of the many possible reasons for this result,

we are currently examining the hypothesis that the nickel layer damps the thermal-stress-induced shock by providing a graduated shock-impedance layer, thus, in effect, spreading the pulse energy absorption over the long-term heating and cooling cycle. We are conducting additional experiments to reproduce and verify these unexpected results as part of our continuing work on refractory coatings.

Gun-barrel erosion can also be controlled by altering the thin gas boundary layer adjacent to the metal surface. Most of the gas in the firing chamber is very hot and turbulent, but the gas in contact with the initially cool barrel surface is relatively cool and almost stationary. The rate at which heat can be delivered to the erosion mechanisms at the metal surface depends on the temperature gradient, which in turn depends on the thickness of the gas boundary layer. Therefore, thickening the gas boundary layer should help to reduce erosion of the gun barrel. We have determined, both experimentally and theoretically, that adding submicron-sized particles of talc, silica, or titanium dioxide to the turbulent combustion gas thickens the boundary layer, thereby reducing the temperature gradient and the corresponding heat transfer. We are able to analyze this turbulent gas with the aid of Schlieren optics, advanced laser-doppler anemometry, and TRAVIS, a computationally efficient turbulent-gas-dynamics code that permits us for the first time to include the large number of variables necessary to describe time-dependent turbulent flow adequately.

Shock-Wave Studies for Modeling the Giant Planets

LLNL has a long-standing research program using shock-wave experiments and theory to provide equation-of-state data for many elements and materials over a broad range of pressures and temperatures. These methods, developed by the Physics Department for DOE defense programs, have proved useful also for modeling the giant planets.

The recent flights of Pioneer and Voyager to Jupiter and Saturn, as well as the anticipated visits to Uranus and Neptune, have stimulated interest in the struc-

ture of these planets. They are known to differ markedly from the well-studied inner planets, and observations of their average density, gravitational moments, and atmospheric composition have enabled researchers to draw some conclusions as to their structure. However, these efforts are hampered by the lack of accurate data on the chemical, physical, and thermodynamic properties of the constituent materials at the extremely high temperatures and pressures characteristic of the planetary interiors.

At the present time, the giant planets are thought to consist of three layers: a top layer of molecular hydrogen and helium; a middle layer of either metallic hydrogen and helium (for Jupiter and Saturn) or icy water, methane, and ammonia (for Uranus and Neptune); and a rocky core of iron, nickel, silicon, and magnesium oxides. To create structural models that correctly predict the observed characteristics of these giant planets, we must have accurate equations of state, phase diagrams, and electrical conductivities for all these materials over an extremely wide range of physical conditions. (An equation of state defines the relationship of pressure, density, and temperature for a given material.)

The water and methane environments of Uranus and Neptune resemble the ultimate product of high-explosive detonation, and the abundance of hydrogen and helium on the giant planets makes them interesting to researchers working on fusion devices. Recently conducted shock-wave experiments have enabled us to develop more accurate equations of state for many of the giant-planet materials, and these equations of state have, in turn, made models of the giant planets more accurate.⁴

Most of the shock-wave data used to model the giant planets were obtained with the LLNL two-stage gas gun. This device can accelerate a 20-g metal projectile against a target at velocities up to 8 km/s. To achieve conditions comparable to those in the planetary interiors, hydrogen, methane, ammonia, and water must be shocked from their liquid phase. The first three materials have boiling points below room temperature, and thus these targets are actually small cryostats.

When the projectile hits the target, it generates a high-pressure shock wave that momentarily compresses and heats the target material (i.e., Hugoniot compression) into the pressure-temperature region of interest. The properties of the material are measured during this brief instant. To obtain even higher pressures, we use a reflected-shock technique in which the primary shock is passed through the target material and then reflected off an anvil (e.g., a brass plate). As the reflected shock wave passes back through the target, it further compresses the target material. By carrying out a series of reflected-shock experiments, it is possible to widen the range of our experimental data, and make subsequent theoretical extensions of the curves more accurate.

Using experimental and theoretical techniques, we have explored the thermodynamic properties of the basic constituent materials of the giant planets, thus making available the data for more accurate models of planetary structure. We recently conducted single-shock experiments on deuterium that obtained pressures up to 20 GPa (0.2 Mbar) and reflected-shock experiments that reached

To create structural models that correctly predict the observed characteristics of the giant planets, we must have accurate equations of state, phase diagrams, and electrical conductivities for their materials over a wide range of physical conditions.

Fig. 2

The heterodyne surface profilometer we have recently developed uses a split laser beam to measure surface irregularities on highly polished optical surfaces. Surface variations of as little as 0.1 nm can be detected from the shift in phase between the two halves of the beam when one half of the beam is focused as a fixed reference point (A) on the optical surface to be measured, and the other half (B) describes a circular path on the surface as the sample rotates.

We set out to develop a noncontacting, non-destructive instrument that would measure the roughness of an optical surface to an ultimate sensitivity of 0.1 nm.

80 GPa (0.8 Mbar) and 7000 K. We have also planned two more reflected-shock experiments on deuterium that will reach pressures between 20 and 80 GPa.

More accurate models of the giant planets await further theoretical research on the metallic phase transition and thermodynamics of dense hydrogen and hydrogen-helium mixtures (including the solubility of helium in hydrogen), the opacity of dense hydrogen, and the chemistry of ice and rocky-core components at high pressures and temperatures. Experimental work currently being planned and conducted at LLNL in relation to defense programs will help theoreticians and physicists to understand these phenomena in relation to the giant planets as well as in high-explosive detonations and nuclear fusion in general.

Optical Surface Profilometry

In the manufacture of precision optical prisms, lenses, and mirrors, two features of the optical surface—its shape and its finish—must be carefully controlled. The grinding and polishing processes normally used to create these surfaces cannot be predetermined quantitatively by a numerical model or technique, so optics must be repeatedly polished and tested until the desired surface is obtained. We can measure the shape of the surface satisfactorily with existing mechanical stylus instruments or by means of optical interferometry, but measuring its finish is more problematic. Techniques currently used are often cumbersome, slow, and insufficiently sensitive. They rely on statistical measurement of the surface (scatterometry), or they require that the surface be coated, contacted, or compared to a reference whose properties are similar and also unknown.

Optical surface finish, or roughness, and the ability to measure it precisely, are important when the optic is required to have a low stray light level and to resist damage from laser radiation. These requirements apply, for instance, to components for inertial confinement fusion laser sources, astronomical systems, high-quality imaging and surveillance systems, and other high-precision applications.

The LLNL Materials Fabrication Division optics group under the auspices of

Fig. 4

Institutions engaged in research on magnetic fusion energy throughout the country are connected by a computer network headquartered in the National Magnetic Fusion Energy Computer Center at LLNL. The network makes the powerful Cray-1 and CDC 7600 computers at the Center available to network members. It also pools and standardizes computer modeling codes developed throughout the national fusion community and makes them easily available to participating institutions.

We are currently working to adapt it for use on curved surfaces, in the expectation that eventually it may be applied to spherical or aspherical lens geometries or even to surfaces other than optical ones.

The National MFE Computer Center

The National Magnetic Fusion Energy Computer Center (MFECC), with headquarters at LLNL, was established in 1974 by the Atomic Energy Commission and is now sponsored by the DOE Office of Magnetic Fusion Energy to make state-of-the-art computational hardware and techniques available to researchers attempting to harness thermonuclear fusion. Access to this national computer network (represented in Fig. 4) enables participating institutions to exchange and standardize computer codes they have developed to model various fusion plasma phenomena. The network allows codes developed at one member laboratory to be applied to experiments under way at another and gives participants access to the Center's high-speed Cray-1 and CDC 7600 computers. Its efficiency in calculating and dispersing results within the national fusion community has made

it crucial to the continuing refinement of fusion theory and the growing ability to predict fusion experiments.

Users can access the large computers in several different ways. Service centers at Princeton University, Oak Ridge and Los Alamos National Laboratories, General Atomic Company, and LLNL are equipped with DEC-10 computer systems that provide direct, high-speed access to the National Center through dedicated wide-band data communications links. A dial-up capability is provided at approximately 30 selected universities and laboratories engaged in magnetic fusion energy research. In addition, 15 remote job-entry stations are in operation at sites designated by the DOE.

The National MFECC has close ties with the Los Alamos and LLNL computer centers, and these ties have been strengthened this year. Cray timesharing systems at the three facilities have been standardized, and common utility routines have been adjusted to make them more portable. The MFECC on-line documentation system is being reviewed at Los Alamos, and the formatting and content of many LLNL Computer Center documents have been adjusted to make them compatible with the MFECC

documentation system, MFECC and LLNL compiler experts are working this year to extend FORTRAN syntax to array processing. Their report⁷ has been reviewed and approved by Los Alamos, LLNL, and the MFECC.

A 56-kilobit/s satellite link between the MFECC and the Princeton Plasma Physics Laboratory was established in April 1981. The performance specified for this system permitted an error rate of 1 bit in 10^9 bits over a 24-hour period and availability of 99.8% over a one-year period. Early experience with the link suggests performance well within these limits. The satellite service replaces a 50-kilobit/s dedicated Bell System line which had been in use since 1976. The 50-kilobit/s Bell System lines to Oak Ridge National Laboratory, Los Alamos National Laboratory, and General Atomic Company continue to operate, but they, too, will be replaced with satellite service by November 1981.

Summary

A sampling of recent achievements by LLNL support organizations indicates their diversity, their technical sophistication, and their importance. Studies of Kevlar fibers should extend the usefulness of Kevlar/epoxy fiber composites in many applications where lightweight, high-strength materials are needed. Our mathematical description of light propagation in optical fibers provides a powerful tool for understanding the basic properties of waveguides and should lead to a variety of practical applications. Studies of mechanisms influencing gun-barrel erosion have revealed a number of ways of controlling this destructive phenomenon. LLNL shock-wave research is deepening our understanding of the processes of fusion and high-explosive detonation and of the structure of the giant planets. *Industrial Research/Development* magazine has recognized our optical surface profilometer as one of the 100 most significant technical products of the year. Our National Magnetic Fusion Energy Computer Center is crucial to the continuing refinement of fusion theory and the growing ability to predict the behavior of confined plasmas. ■

Key Words: computer; fiber optics; giant planets; gun-barrel erosion; Kevlar fibers; Kevlar epoxy composites; light propagation; magnetic fusion energy; matrix organization; modeling; National Magnetic Fusion Energy Computer Center; optical fibers; optical surface profilometry; shock-wave studies; TRAVIS.

Notes and References

1. See, for example: R. J. Morgan et al., "The Structure and Property Relationships of Poly(p-Phenylene Terephthalamide) Fibers," *Polymer Preprints*, American Chemical Society 21(2), 264 (1980); R. J. Morgan et al., "The Failure Modes and Durability of Kevlar-Epoxy Composites," in *Proc. 12th Natl. SAMPE Tech. Conf.* (1980), p. 361, and C. O. Pruneda et al., "Structure Property Relations of Kevlar-49 Fibers," *American Chemical Society Polymer Preprints* 22(2), in press.
2. "Light Propagation in Optical Fibers," *Energy and Technology Review*, UCRL-52000-81-3, March 1981, p. 1.
3. "Research on Gun-Barrel Erosion Mechanisms," *Energy and Technology Review*, UCRL-52000-79-1, January 1979, p. 9, and "Mechanisms Influencing Gun-Barrel Erosion," *Energy and Technology Review*, UCRL-52000-81-3, March 1981, p. 11.
4. "Shock-Wave Studies: Modeling the Giant Planets," *Energy and Technology Review*, UCRL-52000-81-4, April 1980, p. 1.
5. G. E. Sommargren, "Optical Heterodyne Profilometry," *Appl. Opt.* 20, 610 (1981).
6. See award announcement in *Industrial Research/Development* 22, 128 (1980).
7. C. Witherell, *Array Processing for FORTRAN*, Lawrence Livermore National Laboratory, UCID-30175 Rev. 1 (1980).

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