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About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to conduct nuclear weapons and controlled thermonuclear reaction research. Today, about 60% of our resources are devoted to defense programs, which include weapons and laser fusion research. Other major areas of focus are: magnetic fusion energy; laser isotope separation; chemistry, engineering, and physics research; biomedical and environmental sciences; applied energy technology; and work for other Federal agencies. The *Energy and Technology Review* is published monthly to report on accomplishments in unclassified programs. A companion journal, the *Research Monthly*, reports on weapons research and other classified programs. Titles from recent issues of the *Energy and Technology Review* are listed opposite the inside back cover.

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Energy and Technology Review

Lawrence Livermore National Laboratory

September 1982

30 Years of Technical Excellence ii

The LLNL-Nevada Organization 1

Over the years, the LLNL-Nevada organization has provided invaluable support to the Laboratory's nuclear test program and other activities at the Nevada Test Site.

Project Plowshare: A Brief History 13

The Plowshare program was established in 1957 to explore the potential of nuclear explosives for civil uses.

Chemistry and Materials Science in Retrospect 21

The Chemistry and Materials Science Department, in support of LLNL's nuclear weapons program, has made numerous technical innovations and has developed many new materials and analysis methods.

Computing at LLNL 28

From the day the Laboratory opened its doors, 30 years ago, we have used the most advanced machines of each generation of computers, devised computational techniques for a variety of scientific disciplines, and designed and implemented new computer systems that are among the most innovative concepts of their time.

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269

This issue of *Energy and Technology Review* is the first of two commemorating the 30th anniversary of the Lawrence Livermore National Laboratory. Here, we review the early history of the Laboratory and many of its original programs; the status of several of our current programs will be reviewed next month. From this historical perspective, we highlight the important elements of the Laboratory's present technical and scientific capabilities that evolved from this early work.

The first article concerns the underground nuclear weapons testing program and some of the early activities of the Laboratory's Nevada organization. The diversity of projects fielded by the LLNL-Nevada people is characteristic of the Laboratory as a whole, and many of our earliest field experiments have led to new technologies that resulted in entirely new programs. For example, many of the skills and technical capabilities first developed for underground weapons testing were later applied to the Plowshare Program for the peaceful application of nuclear explosives. Similarly, capabilities developed under the Plowshare Program in rock mechanics, seismic and shock wave modeling, and field measurements and operations were later applied to energy research and development programs such as geothermal energy, underground coal gasification, and oil shale recovery. Even more specialized spin-offs from our underground testing programs have benefited the research of both the Nuclear Regulatory Commission

Thirty Years of T

and the Department of Energy in the underground storage of commercial reactor waste.

The Lawrence Livermore National Laboratory is a multiprogram, multidisciplinary laboratory, and many of our current technical and scientific disciplines originated in the first days of the Laboratory. An article in this issue describes our Chemistry and Materials Science capabilities and how these support and enhance the Laboratory's activities. A companion article on developments in computers and computing science presents another important technical discipline. The mathematical modeling of complex physical phenomena is central to many of our research and development programs. Whether in the development of nuclear weapons or in energy or environmental science research, we test our theories on computers before testing them in the field. Our continuing development of large, high-speed computers has been a vital facet of our ability to solve significant national problems. Such capabilities go hand in hand with our expertise in chemistry and other scientific disciplines, as well as with our experimental advances in the field. The history of these aspects of the Laboratory's experience tells the story of many of the successes that have made us one of the world's leading scientific laboratories.

Philip E. Coyle, III
Associate Director for
Nuclear Testing

Technical Excellence

The LLNL-Nevada

Organization

Developing modern and effective nuclear weapons requires a vigorous research, development, and test effort. Over the years, the LLNL-Nevada organization has provided essential support to the laboratory's weapons program and other activities of the laboratory.

In 1950, the U.S. Atomic Energy Commission (AEC) designated a 1680-km² area in the arid terrain of the Nevada desert as the nation's test site for its nuclear weapons program.¹ (Many of the colorful names in the area—Jackass Flats, Skull Mountain, Buckboard Mesa, and Frenchman Flat—reflect Nevada's early mining days.) Later annexations increased the size of the Nevada Test Site (NTS) to its present 3500 km². In 1956, the Laboratory established an organization to support its activities at the NTS. By April 1957, the initial cadre of the LLNL-Nevada organization had moved into its headquarters in Las Vegas.

Programs transferred to the newly chartered entity were generally those that could not be conducted at Berkeley, Livermore, or Site 300 (about 25 km southeast of Livermore) for reasons of safety or economics. From an original complement of 14, personnel assigned to or recruited for the Nevada organization grew to a peak of more than 300 in 1964. Subsequent program terminations and changing requirements have reduced this number to its present level of slightly over 100. Here, we review,

The Nevada Test Site, located in the arid terrain of southwestern Nevada, is the national test site for this country's nuclear weapons program.

in chronological order, some of the highlights of the organization's activities since its inception.

The Early Years

During its early years, as now, many of LLNL-Nevada's activities supported weapons testing programs. Public concern at that time was beginning to focus on the health effects of fallout from the atmospheric testing of nuclear weapons. The Laboratory responded by exploring the technical feasibility of conducting underground nuclear tests (see the box on p. 4). In Project Rainier, conducted in September 1957, we tunneled into the Rainier Mesa to provide an emplacement hole for a 1.7-kt event. Diagnostic data gathered on the Rainier Event included temperature and radiation measurements. Following the detonation, we re-mined the tunnel to perform geological studies and to measure cavity dimensions and movement of material. These data verified that Rainier was the first nuclear test contained completely underground; no radioactivity was released to the atmosphere. At another location, we undertook an experimental drilling program in support of underground testing technology. This effort resulted in the development of many new techniques for line-of-sight drilling.

During this period, we also conducted nuclear device studies at Yucca Lake, a dry lake bed at Yucca Flat. In one project, shells from a 155-mm howitzer were fired almost vertically upward to study the stresses induced in various components. To retrieve the shells intact, we plowed more than 18 000 m² of the lake bed to a depth of nearly 2 m (because of uncertainty in the exact points of impact). Later studies in the same project required plowing the lake bed to a depth of 3.7 m over an area nearly 200 m in diameter.

Among the nuclear tests during this period was a series known as Operation Hardtack, Phase II (Phase I took place at the Enewetak Proving Ground in the Pacific). Conducted in the fall of 1958, Hardtack, Phase II, was notable for being the last series of weapons

tests conducted before the U.S.-Soviet moratorium on atmospheric nuclear testing went into effect on October 30, 1958. The short preparation period, the large number of weapons detonated, and the accelerated test schedule presented a hectic challenge to the Laboratory's Nevada organization.

The Hardtack II series had several objectives, among them to test new physics applications in weaponry and to provide proof tests of stockpile weapons before final design acceptance. Some of the detonations were conducted underground; these tests gave us additional experience in developing drilling technology, in diagnostic techniques, and in post-test recovery of diagnostic equipment. We also developed an extremely accurate optical technique for surveying vertical drill holes ranging from 40 to 90 cm in diameter. The technique was proved to be accurate to within 1 cm at a depth of 300 m.

Because of the impending moratorium, the Hardtack II series became a race against the clock, conducted in one-fourth the time of any previous test operation. With LLNL's participation, 37 nuclear devices were detonated in 50 days, including four within a 24-hour period. At midnight on October 30 (the deadline for the moratorium), the last device was still hanging, unexpended, from a balloon.

The Test Moratorium

During the period of the test moratorium, which lasted through September of 1961, LLNL-Nevada continued its supporting activities at a reduced level. Much of our effort during this time focused on two major programs: Project Pluto and Project Plowshare (see the article beginning on p. 13).

Project Pluto

The objective of Project Pluto was to develop a unique nuclear reactor, designed to propel a missile through the atmosphere at altitudes ranging from sea level to several miles at a velocity three times the speed of sound. In building the reactor, Laboratory scientists and engineers pioneered new technologies in engineering, nuclear physics, and chemistry. The result was a reactor core incorporating several hundred thousand fuel elements consisting of a mixture of highly enriched uranium oxide and beryllium oxide (an account of the development of the reactor's fuel elements begins on p. 22).

The propulsion system operated on the ramjet principle: enormous quantities of air were ingested, heated by the reactor, and expelled at high temperature and pressure to provide thrust. The Laboratory designed, built, and successfully tested three Project Pluto reactors—an early test bed known as

Timeline highlighting U.S. policy decisions concerning nuclear weapons testing and corresponding activities of the LLNL-Nevada organization.

Nuclear Testing at the

Underground nuclear testing is a complex procedure involving much more than simply burying a device in a hole and detonating it. In fact, most devices are not weapons. Some devices were developed specifically for Project Plowshare experiments to adapt nuclear explosives to peaceful purposes. Others are dedicated experiments designed to probe the physics of nuclear explosives. Even after successful testing, a device intended for a weapon application must undergo further development engineering, a process called weaponization, and possibly further proof tests.

For a nuclear test, a site first is carefully selected to ensure that no accidental venting (release of radioactive materials to the atmosphere) occurs as a result of local earthquake fault zones, soil materials, or other geological features. This often requires detailed knowledge of the geology of the test site. Very large drill bits are required to bore the emplacement hole, which can be as deep as 2 km, depending on the yield of the device to be tested (Fig. a). We use special photographic and other recording equipment to examine the walls of a test hole and to retrieve samples of wall materials for laboratory analysis. The resulting downhole logs are used to make further decisions regarding the safety of the site.

When a hole has been drilled to the required depth, a process that takes several weeks, it is ready for emplacement of the device (Fig. b). Each device to be tested is accompanied by a large diagnostics canister (Fig. c) containing the instruments to measure and transmit vital data at the instant of detonation. Because many of the electronic and mechanical instruments are structurally fragile and extremely sensitive, or involve critical alignments, we must take special pains to ensure their integrity while they are lowered into the hole. Some test data are transmitted through heavy cables attached to the diagnostics canister to recording instruments housed in trailers on the surface. The compact bundles of cables must be

Nevada Test Site

reach several hundred tonne, requiring heavy cranes to perform the emplacement operation.

After a device is emplaced, we must backfill the hole (an operation called stemming) with several types of natural and artificial materials. This is still another precaution to ensure that the detonation—called an event—is safely contained. This process is also very time consuming. After stemming is completed, every event is preceded by days of dry-run countdowns, during which the firing, recording, and safety equipment is thoroughly tested.

At the instant of detonation, a large volume of various kinds of complex data, called prompt diagnostics, must be transmitted and recorded in minute fractions of a second before the instrumentation is destroyed by the explosion (Fig. d). When a device detonates, it creates a large underground cavity, the bottom of which quickly fills with molten rock material and debris. As the heat and pressure subside, material begins to fall into the cavity, creating a void that progressively works its way up (Fig. e). If the void reaches the surface, the overlying rock collapses under its own weight, producing a large collapse crater (Fig. f). Following an event, radiation-detecting and listening devices provide information on conditions in and around the test hole, including the formation of the collapse crater. The condition of the test site is simultaneously monitored from the air by helicopters.

The testing process does not end here, however. To collect samples of radioactive gases and solid debris produced by the explosion, we must drill another hole at an angle to the emplacement hole to provide a channel for the retrieval devices, another lengthy procedure (see Fig. e). These post-test samples are sent to special laboratories for radiochemical analysis. Finally, as an additional safety measure, sites of previous events are monitored periodically for radiation levels and other potential hazards.

carefully arranged to ensure that no void channels, through which radioactive gases might travel, remain after the hole is filled. The net weight of all this equipment, including the device, the diagnostics canister, and the cables, can

Tory II C reactor built for Project Pluto, a large-scale program to develop a nuclear ramjet engine. The reactor was assembled and successfully tested at the Nevada Test Site in the early 1960s.

the Hot Box, a full-scale, earth-bound version known as the Tory IIA, and a "flyable" version called the Tory IIC.

The Hot Box consisted of stacks of graphite blocks interspersed with small numbers of oralloy (uranium-235) foils. To obtain initial test data, we first heated air to high temperatures (between 600 and 650°C). The heated air was then circulated through the reactor. LLNL-Nevada tested much of the equipment associated with this facility, including air compressors, high-pressure piping, valves, and furnace and heat-storage systems. Results from the Hot Box tests were used to design the Tory IIA reactor.

From 1960 through 1961, the Nevada organization's activities in support of the Tory IIA reactor ranged from the preparation of facilities and testing through the removal and disassembly of the reactor core. Primary support consisted of installing and checking all electronic and mechanical systems, including nuclear controls, air-supply systems, data-acquisition and recording instruments, closed-circuit television, and remote-handling equipment for disassembling the core. Because the fuel elements were loaded into the reactor in an assembly building almost 2 km from the test site, it was necessary to install railroad tracks, switching equipment, and associated rolling stock to move the reactor to the test facility and then to return it to the assembly

building after completion of testing. Railroad operations were run under remote control. We also devised and installed a system for remotely monitoring radiation around the test perimeter.

To simulate the flow of air through the reactor, we built extensive facilities at the NTS that included a huge "tank farm" consisting of several kilometres of casing pipes for the high-pressure air supply. The piping was installed in a space nearly a kilometre long and more than 60 m wide. The tank farm had an initial capacity of more than 60 tonne of air. The air was heated by passage through parallel pebble-bed heaters filled with ball bearings and weighing a total of 100 tonne.

The Tory IIA reactor was tested successfully several times at high power for periods close to two minutes. After final testing, the reactor was cooled down, remotely disassembled and inspected, and its fuel elements were sent to Livermore for detailed analysis.

The "flyable" version of the Pluto reactor, the Tory IIC, generated 600 MW of power—about half the power capacity of Hoover Dam—and operated at temperatures over 1000°C. To simulate actual flying conditions for the reactor's power test, we enlarged the existing tank farm to a capacity of 600 tonne of compressed air stored under a pressure of nearly 25 MPa. The reactor was mounted on a railroad flatcar in a bunker. During testing, nearly a tonne of

air, heated to over 500°C, poured through the reactor every second. Although the reactor was unshielded, the radiation it emitted during operation was confined to the test area.

All six tests of the two Tory reactors were conducted without a failure. The lack of a firm military requirement eventually ended Project Pluto in 1964, but the advanced technology it embodied proved an outstanding success.

Project Plowshare

During the testing moratorium, the Nevada organization also began activities associated with Project Plowshare, a large-scale effort to adapt nuclear explosives to peaceful purposes such as the excavation of canals and harbors (see the article beginning on p. 13). These consisted primarily of high-explosive experiments to investigate the behavior of various earth materials and to develop scaling laws.

Resumption of Testing

When the Soviet Union broke the testing moratorium in September 1961 with an extensive, unannounced series of large atmospheric nuclear tests, the

United States resumed its own nuclear testing program underground at the NTS (and later, some atmospheric testing in the Pacific). LLNL-Nevada's activities in support of weapons programs at this time included locating sites for drill holes, deciding on their drill depth, recording geological and other data from exploratory holes, mapping all underground workings, and recovering post-test samples from underground events.

The resumption of testing also prompted us to develop a new support system for the protection of personnel. The RAMS (remote-area monitoring system) was designed to detect, display, and record at a remote control point any radiation released around the site of an event, indicating when the site could be safely re-entered.

A common phenomenon associated with underground testing is the formation of the collapse crater following a detonation. (A collapse crater results when overlying material falls into the void created by an explosion, producing a large crater if the collapse column reaches the ground surface.) A seismic detection and geophone listening

Yucca Flat at the Nevada Test Site, looking southeast. The whitish expanse in the upper center of the picture is Yucca Lake, a salt flat. Yucca Flat is the site of many underground nuclear tests; note in the foreground the collapse craters from various tests.

system placed near the site enables us to determine when the infall of material stops and the collapse crater forms. During this period, the Nevada organization was responsible for operating both the RAMS and the safety geophone system.

In addition to supporting weapons tests during this period, the Nevada organization participated in all Project Plowshare experiments, including those using nuclear explosives. One of these was Project Gnome, a 3.1-kt device detonated at a depth of 360 m in Carlsbad, New Mexico, in December 1961. Gnome was fielded to study the feasibility of using a deeply buried explosion for power recovery, isotope production, and scientific nuclear experiments. Information acquired from the Gnome Event enabled us to develop a new system for measuring radiation and temperatures generated by underground tests. The system simultaneously measured temperatures up to 300°C and radiation fields as high as 1000 R/hour. We also modified a television camera system to photograph the Gnome cavity.

Another Plowshare effort was Project Dribble, a series of nuclear seismic experiments conducted near Hattiesburg, Mississippi. Several LLNL-Nevada personnel were assigned to help install and calibrate the RAMS and safety geophone systems for the event and to make post-test geophysi-

cal measurements that included cavity size and underground temperature and radiation levels.

During this time, high-speed flare photography techniques were developed to improve measurements of earth velocities produced by Plowshare experiments at the NTS. Other Plowshare experiments were designed to test the feasibility of large-scale earth excavation. Nevada personnel provided support for the Danny Boy, Scooter, and Sedan Events conducted at the NTS, the last of which was a very large excavation experiment. In the Sedan Event, a 100-kt device buried at a depth of 200 m produced a crater 340 m across and 100 m deep.

In addition to its weapons-testing activities and participation in Project Plowshare, the LLNL-Nevada organization supported the construction, assembly, and initial operation of Super-Kukla, a prompt-burst neutron-pulse reactor. Located in a shielded containment bunker in a remote area of the NTS, the reactor was designed to serve as a neutron source for irradiating a variety of test specimens, including fissile material used in weapon components. A separate building housed the control room. Continuous reactivity was controlled by moving six individually operated fuel rods into holes in the reactor core. To generate neutron bursts, six ganged fuel rods were inserted into the core to provide a step change in reactivity. Burst activity was terminated by separating the core into two roughly equal segments. Nominal power bursts exposed samples in the reactor cavity to about 10^{15} neutrons/cm², causing core temperatures to rise by some 250°C. The burst repetition rate was governed primarily by the core cooling time of 4 to 6 hours. The Super-Kukla reactor was shut down and dismantled in 1978.

Over the decade from 1965 through 1975, the Nevada organization continued its support for weapons testing activities at the NTS. In addition, we provided operational support for the Cannikin Event conducted in Amchitka, Alaska, in 1971. This event, detonated at a depth of 1830 m and designed with a yield of roughly 5 Mt,

Diagnostics package in place for a tunnel event.

Mercury, Nevada, headquarters for LLNL-Nevada's test site operations.

was a test of the warhead for the Spartan antiballistic missile system.

Expansion of LLNL-Nevada Facilities

In April of 1964, the Laboratory occupied its new headquarters building at Mercury, an area at the southeastern corner of the NTS containing administrative, service, and storage facilities. Known as the Blue Building, the 3500-m², single-story structure houses administrative offices, a health physics laboratory, a photo laboratory, and electronics and mechanical shops. The building appreciably increased the Nevada organization's technical support capabilities. A later addition to the Blue Building was a gamma-ray spectroscopy facility for selecting and analyzing material from core samples recovered during post-test drilling operations. It includes two germanium gamma-ray detectors, a computerized data-analysis system, a lead-shielded storage area, a glove box, and a small "hot cell" for examining radioactive materials with remotely controlled manipulators. The facility has greatly reduced both post-test standby time for drilling operations and the quantity of

radioactive materials shipped to Livermore for analysis.

In recent years, the Nevada organization's facilities at the NTS have undergone significant expansion and modernization. In 1975, we occupied the new CADAC (Control and Data Acquisition Center) facility, located in an area northwest of Mercury. CADAC centralizes all the Laboratory's timing, firing, and data-handling activities in support of its weapons-testing program.

In 1976, we completed the North Las Vegas ATLAS (Augmented Test Logistic Assembly System) facility. ATLAS enables us to carry out complete fabrication and testing of the Laboratory's instrumentation systems for weapons experiments before moving them to the NTS. The tested systems are delivered to the NTS assembled and ready for attachment to a nuclear device. The ATLAS facility comprises about 12 000 m² of floor space distributed among three main buildings and several smaller structures. A 30-m tower emplaced over a hole 30 m deep and nearly 4 m in diameter provides structural support for diagnostics canisters.

In 1981, we installed a high bay in our Mercury headquarters to assemble

logging tools (instruments used to record geological and other features of emplacement holes). The assembly bay enables us to calibrate specialized experimental logging tools and cameras for subsequent testing in a downhole environment. The bay includes a calibration hole 37 m deep and 3 m in diameter.

LLNL-Nevada's Innovative Instrumentation

The Monster

The evolving demands of our testing programs require the continual development of new or improved instrumentation. During 1975, for example, we designed and constructed a piece of equipment dubbed the Monster. The Monster was developed to retrieve containers of radioactive tracer materials from among a thicket of cables and pipes at the bottom of a very deep event hole. (The tracers are used to provide information on specific chemical and physical phenomena occurring during the event.) The system weighs 0.5 tonne and is powered by 23 motors controlled through television monitors

Underground nuclear tests require many kilometres of heavy cable to transmit diagnostic data from an event to recording instruments located in trailers on the surface.

at the surface. At the bottom of the hole, a moveable television camera attached to one of the Monster's arms transmits pictures of the operation to the monitors while another arm saws off the tracer containers, which are bolted into the hole with thick metal fixtures. The containers are collected by the Monster before it returns to the surface. The Monster has also been used to saw off sections of pipe up to 12 m long. In addition to its saw, the Monster carries a grinding wheel used to smooth sharp bolts and other protrusions. Guided by the downhole television camera, the control system at the surface can make corrections of 0.6 cm at a depth of over 1500 m.

The Fisheye Camera

Another recent innovation is a fish-eye camera for surveying geological features of emplacement holes. Providing a 360-deg panoramic view of the sidewalls, the camera takes pictures automatically at preset distance intervals using depth-sensing circuitry. Lighting is provided by a xenon-tube lamp and reflector assembly. The supporting framework of the camera is designed to maintain its alignment within the hole and to protect it from water condensate and debris. Because the camera's film data are so clear and easy to interpret, it has been adopted as a standard system for evaluating the geology of NTS boreholes.

The Remotely Controlled Camera System

This year, we completed development of a remotely controlled camera system that can be lowered many metres through a small, rocky hole drilled at an angle to the plane of the ground surface. The system takes both still photographs and television pictures. The requirement for such a camera arose when a recent underground nuclear event failed to develop a collapse crater, and we needed to know why. Because a crater might have formed belatedly at any time, it was necessary to drill the camera hole on a slant some distance from the event hole. To enable the camera system to

traverse the uncased hole, we mounted it on an articulated arm having a shoulder, a wrist, and an elbow. The camera package is less than 22 cm in diameter, yet contains a standard 35-mm Pentax camera, a television camera, and a lighting system. The cameras are linked through a computer control that matches the focus and zoom settings of the two cameras. In 1981, this system won a first place for its designer in the Professional Photographers of America Awards for Technical Photography.

Recent Uses of LLNL-Nevada's Facilities and Expertise

The Threshold Test Ban Treaty of 1974 and the Peaceful Nuclear Explosions Treaty of 1976 limit to 150 kt weapons tests and tests or applications of peaceful nuclear explosives, respectively. The constraints imposed on test conditions by these treaties provided additional challenges to the Laboratory's role in maintaining and modernizing our nuclear deterrent.

The Nevada organization is playing an important role in the Laboratory's Treaty Verification Program, established in response to the Threshold Test Ban Treaty. The goal of this program is to develop the technical means for monitoring and verifying compliance with present and future treaties limiting or banning nuclear tests. At the NTS and in areas surrounding the test site, studies of seismic verification techniques and tests of seismic monitoring equipment are being conducted; using scheduled nuclear tests at the NTS, a data base of well-characterized events is being compiled for use as an historical basis for responding to challenges under present and future test ban treaties.

The LLNL-Nevada organization is involved in two other projects of note: the Spent Fuel Test and the Liquefied Gaseous Fuels Program. The Spent Fuel Test is a study of the effects of storing spent nuclear reactor fuel, 2.5 years out of the reactor core, in granite. The Climax granite at the NTS provided the appropriate geology and the Nevada

organization provided the necessary technical, logistical, and safety support for the project. This five-year experiment, begun in 1980, is designed to evaluate the feasibility of safe and reliable short-term storage of spent fuel from commercial reactors at a plausible repository depth in common granite, followed by retrieval of the fuel. The data from this study will be used to evaluate granite as a medium for deep geologic storage of highly radioactive waste and to design such a repository in granite.

Lowering diagnostics and device canister into an emplacement hole. The combined weight of the canister and cables can reach several hundred tonne, requiring heavy cranes for the operation.

Drilling for an emplacement hole. Very large drill bits are necessary to bore holes that can range from 1 to 4 m in diameter and up to 1600 m in depth.

The Liquefied Gaseous Fuels Program also is making use of the expertise of the LLNL-Nevada organization. This program is investigating the behavior of spills of large volumes (tens to hundreds of cubic metres) of liquefied gaseous fuels. The experiments require large, remote sites and technical expertise to acquire large amounts of data under hazardous conditions. The data-acquisition systems for these experiments were developed and fielded out of the Nevada organization; the first tests were conducted at China Lake, California. The larger tests required by the program may be beyond the facilities at China Lake; therefore, consideration is being given to developing an LGF test facility at the NTS.

Summary

We have addressed, here, only a few of the many and diversified activities of the LLNL-Nevada organization conducted at the NTS over the past three decades. The Laboratory's support of

the nation's nuclear test program continues today, growing in technical sophistication and versatility. Insofar as it has contributed to the strength and credibility of our nuclear deterrent, the NTS has become a national institution of irreplaceable value. □

Key Words: Augmented Test Logistics Assembly System (ATLAS); Cannikin Event; Control and Data Acquisition Center (CADAC); Danny Boy Event; Dribble; Gnome Event; Hot Box; Limited Nuclear Explosions Treaty; LLNL-Nevada organization; Nevada Test Site (NTS); Operation Plowshare; Peaceful Nuclear Explosions Treaty; Plowshare; Pluto; Rainier Event; remote-area monitoring system (RAMS); Scooter Event; Sedan Event; Super-Kukla reactor; Threshold Test Ban Treaty; Tory IIA; Tory IIC; underground nuclear testing.

Notes and References

1. For a comprehensive description of the geology of the Yucca Flat area of the NTS, see *Energy and Technology Review*, UCRL-52000-82-4 (April 1982), p. 14.

Project Plowshare:

“And they shall beat their swords into plowshares, and their spears into pruning hooks; nation shall not lift up sword against nation, neither shall they learn war any more.”
Isaiah, II,4

The first official recognition of the civil uses of nuclear explosives appeared in the U.S. Atomic Energy Act of 1946, which noted that “atomic energy is capable of application for peaceful as well as military purposes.” Public interest in such applications was aroused initially by the statement of the Soviet delegate to the United Nations, in 1949, that “the Soviet Union is now using atomic energy for

peaceful purposes, not to stockpile bombs. Right now, we are utilizing atomic energy for our economic needs in our own economic interest. We are razing mountains; we are irrigating deserts; we are cutting through the jungle and the tundra; we are spreading life, happiness, prosperity, and welfare in places where human footsteps have not been heard for a thousand years.”¹

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The United States began its own systematic exploration of the potential of nuclear explosives for civil purposes in 1957. Under the leadership of Dr. Harold Brown and with the support of Professor Ernest O. Lawrence and Dr. Edward Teller, a group was formed at the University of California Radiation Laboratory in Livermore to carry out this task. In the same year, the U.S. Atomic Energy Commission (AEC) formally established Project Plowshare.²

The international crisis precipitated by Egypt's seizure of the Suez Canal in 1956 and the long-expressed interest of the Panama Canal Company in excavating a sea-level canal across the American Isthmus placed the initial focus of the Plowshare program on large-scale earth excavation. Although it was obvious from the outset that enormous quantities of material could be displaced with nuclear explosives, it was equally clear that the problem of radioactive release to the atmosphere would have to be solved before a major undertaking was feasible. Accordingly, Plowshare's early concerns were twofold: to reduce radioactive fallout to a minimum and to relate crater dimensions to the size and depth of

placement of explosive charges in a variety of earth materials.

A parallel interest was the prospect of testing nuclear explosives underground. In 1957, the Laboratory's Project Rainier, a 1.7-kt weapon experiment at the Nevada Test Site (NTS), confirmed the feasibility and safety of underground testing. Rainier's success stimulated further interest in the engineering applications of contained explosions. Among the ideas discussed at the Atoms for Peace Conference, held in Geneva in the autumn of 1958, were earthmoving, underground water storage and replenishment of aquifers, shattering and retorting oil shale *in situ*, oil recovery from tar sands, recovery of geothermal heat, power generation from heat deposited in salt or limestone formations, isotope production, and recovery of copper by *in situ* leaching.

Project Gnome

In 1958, a U.S.-Soviet moratorium on nuclear testing halted nuclear experiments connected with Plowshare. During the moratorium, however, comprehensive studies of several projects continued, notably of the Trans-Isthmian Canal. In addition, a

Fig. 1

Cavity produced by the Gnome underground nuclear explosion, the first Plowshare experiment. The 3.1-kt device formed a cavity 23 m high with a diameter of 49 m. Note the man standing in the lower center of the photograph.

Fig. 2

Crater produced by Sedan, the first of Plowshare's excavation experiments. The crater is 365 m in diameter and nearly 100 m deep. The vehicles and equipment in the lower left of the photograph give an idea of scale.

high-explosives cratering program was continued to establish scaling laws and to provide an empirical basis for designing nuclear experiments. During this period, President Eisenhower authorized construction of a site near Carlsbad, New Mexico, in preparation for Project Gnome. Gnome was designed to explore the feasibility of using a deeply buried explosion in a dry salt bed for isotope production, power recovery, and scientific nuclear experiments.

When the Soviet Union broke the moratorium by unilaterally resuming atmospheric nuclear testing in the autumn of 1961, President Kennedy ordered resumption of our own testing program. In addition to resuming weapons tests, the Laboratory conducted Gnome, the first of Plowshare's nuclear experiments, in December 1961. The 3.1-k^t device was detonated at a depth of 360 m, forming a cavity 23 m high with a diameter of 49 m (Fig. 1). The results had several noteworthy features. One was the increase in permeability of the rock surrounding the explosion for one or two cavity radii beyond the collapse region. Such regions are valuable in experiments to stimulate the production of natural gas and of oil

from oil shale. The explosion also produced a brief, high-flux neutron pulse with a clear potential for scientific applications. However, elastic waves generated by the explosion traveled through the surrounding rock with unexpectedly high amplitude and velocity, causing concern for the effects of ground motion on nearby structures. Finally, saturated brine liberated by the detonation hindered attempts to recover thermal energy generated by the experiment.

Excavation Experiments

Because of the Panama Canal Company's interest in a sea-level canal, Plowshare continued to emphasize civil engineering applications. In July of 1962, the Laboratory conducted Sedan, Plowshare's second nuclear experiment. Our largest cratering experiment, Sedan was detonated at the Nevada Test Site (NTS) to study the effects and phenomenology of excavation explosions in alluvial soils. The 100-kt device, having a fission-yield component of less than 30 kt, was buried at a depth of about 200 m and formed an impressive crater 365 m in diameter and nearly 100 m deep (Fig. 2).

In 1964, President Johnson signed a bill providing for "an investigation . . . to determine a site for the construction of a sea-level canal connecting the Atlantic and Pacific Oceans" (Ref. 2, Plowshare Bibliography). Figure 3 shows the alternative routes of the proposed canal. The bill established a special commission to study construction sites and methods, "including the use of nuclear excavation." The resulting report (published in 1970), the most extensive U.S. study of nuclear excavation to date, concluded that "although we are confident that someday nuclear explosions will be used in a wide variety of massive earth-moving projects, no current decision on U.S. canal policy should be made in the expectation that nuclear excavation technology will be available . . ." The major factor in shelving plans for the sea-level canal was that the capacity of the existing canal would not be exceeded until 1995—too far in the future. The recommendation was that nuclear excavation be considered in any future studies.

During this period, we conducted five more low-yield nuclear Plowshare excavation experiments at the NTS to ex-

plore cratering mechanics in different types of dry rock ranging from hard rock to alluvial soil. Of these, Project Buggy in March of 1968 was especially significant. Conducted in basalt, the Buggy experiment consisted of the simultaneous detonation of five 1.1-kt nuclear explosives buried 41 m deep and spaced 46 m apart. The trench produced was 260 m long, 77 m wide, and 20 m deep (Fig. 4). At higher yields, this technique would be well suited to the excavation of canals, harbors, or highway cuts.

Heavy Isotope Production

Between 1962 and 1969, Plowshare also pursued the development of specialized nuclear devices designed to produce new heavy isotopes unobtainable by conventional methods. Such isotopes were expected to open new areas of nuclear physics, to provide nuclides with diagnostic and therapeutic applications in medicine, and to serve as miniature sources of energy.

In one experiment, Hutch, designed to study the production of heavy nuclei by the rapid multiple capture of neutrons, we subjected uranium and thorium targets to a flux of about

Fig. 3

Alternative routes of the Trans-Isthmian Canal, a proposed application of the excavating technology developed by Plowshare.

40 mol/cm² of equivalent 20-keV neutrons (about 10^{25} neutrons per square centimetre of target material). This is the largest neutron flux known to have been produced by man. The experiment generated extraordinarily large quantities of heavy isotopes—for example, about 10^9 times the amount of fermium-257 producible in a reactor—and other rare, heavy radionuclides of an isotopic purity unattainable in a high-flux reactor. An intensive search for new isotopes with mass numbers greater than 257 was unsuccessful, presumably because the spontaneous fission lifetimes of such isotopes are much shorter than the time it took to retrieve debris samples.

Gas Stimulation Experiments

The AEC's support, along with public Plowshare symposia, encouraged private industry to explore the use of nuclear explosives for commercial purposes. In 1967, the first of three joint government-industry field experiments was conducted to investigate the feasibility of stimulating the production of natural gas in low-yield fields with nuclear explosives. Project Gasbuggy was carried out under the technical direction of the Lawrence Radiation Laboratory (at Livermore) with the joint participation of the El Paso Natural Gas Company and the Department of the Interior. The 29-kt experiment was conducted in a sandstone gas-bearing formation in the San Juan Basin, New Mexico, at a depth of about 1300 m (Fig. 5). The detonation produced an underground chimney 102 m high with a diameter of almost 50 m.

The Gasbuggy results were encouraging. Gas production was increased six to eight times over previous rates. In six major production tests (the last in 1973), a total of over 37×10^6 m³ of gas was flared to the atmosphere. Studies of gas quality, however, showed that the concentration of residual tritium (a radioactive isotope) was higher than desirable, underscoring the need to improve the design of the nuclear explosives.

The second Plowshare gas stimulation nuclear experiment, Project Rulison, was conducted near Rifle, Colorado, in September 1969, under the sponsorship of the Austral Oil Company and the technical direction of Los Alamos Scientific Laboratory. A 40-kt nuclear explosive was buried at a depth of about 2570 m in a reservoir with sufficient gas in place to provide a reasonable test of economic feasibility. The explosion produced a chimney somewhat smaller than that of the Gasbuggy experiment. We again found a substantial quantity of tritium in the gas. From Rulison, we learned that it would be necessary to stimulate a much thicker vertical section of the reservoir to produce economic quantities of gas, suggesting the use of multiple explosives.

Our last underground Plowshare field experiment, Project Rio Blanco, took place in northwestern Colorado in May 1973. Sponsored by CER-Geonuclear Corporation and LLNL, this project entailed the simultaneous detonation of three 30-kt nuclear explosives spaced over an interval of about 260 m from a depth of nearly 2000 m. Reflecting experience gained from Rulison, we designed and developed the explosives to minimize their diameter, the tritium yield, and the

Fig. 4

Crater produced by the Buggy experiment, a demonstration of nuclear excavation technology. Five 1.1-kt explosives were spaced 46 m apart to produce a trench 260 m long and 77 m wide. The small object at the lower right end of the crater is a truck.

Fig. 5

Lowering the nuclear explosive into the test hole for the Gasbuggy experiment. Designed to liberate natural gas from a sandstone formation, Gasbuggy increased gas production six times over previous rates.

operational costs of the project. The explosive yield was tailored to the thickness of the surrounding geological structure. We also designed and built an integrated system for command, control, and monitoring of the experiment. Although the explosives were intended to produce a single, interconnected chimney, this aspect of the experiment was unsuccessful, and the resulting cavities were unconnected. Consequently, we obtained only small amounts of gas from the upper cavity. Subsequent tests revealed that the site chosen for the Rio Blanco experiment had a much lower permeability and gas quality than expected, making production testing impractical.

Although the Gasbuggy, Rulison, and Rio Blanco experiments provided invaluable experience and established the technical feasibility of gas stimulation techniques using nuclear explosives, its economic viability was never demonstrated. Because federal policy required private industry to fund 90% of the costs, and because sites were limited to low-production fields, incentives to undertake further gas-stimulation experiments were weak. No gas from the experimental wells has been marketed.

Other Potential Applications

During the life of Project Plowshare, we studied a number of additional applications of nuclear explosives, although none of these was tested in the field. The Project Bronco study, carried out by CER-Geonuclear Corporation (representing a score of oil companies) with the participation of the AEC, the Bureau of Mines, and the Livermore Laboratory, explored the use of nuclear explosives to fracture oil shale. The oil was to have been recovered by an *in situ* retorting process. Although a contract was negotiated in 1968, financial and patent disagreements among the participants aborted the project. However, the government continued research on the retorting phase of the plan, using simulated *in situ* retorts containing up to 150 tonnes of oil shale (Fig. 6). The success of this effort led to its adaption to current *in situ* recovery procedures, suitably modified for conventional high explosives and mining techniques.

Another study investigated the use of nuclear explosions to produce an underground cavity for storing liquid or gaseous hydrocarbons in an impermeable formation such as salt, shale, or crystalline rock. Studies conducted with the Kennecott Copper Company investigated the feasibility of fracturing a copper ore deposit with nuclear explosives and recovering the ore by *in situ* leaching. Also studied was the possibility of creating nuclear chimneys in deep impermeable rock for disposal of high- and low-level radioactive wastes from fuel reprocessing plants.

Fig. 6

Scaled-down retort used by LLNL to demonstrate the feasibility of *in situ* retorting of oil shale fractured by nuclear explosives. Although a Plowshare oil-shale project has never been carried out, the retorting technology developed is currently used in conventional oil-shale efforts. The retort shown has a capacity of 6.6 tonne.

Many other applications of civil nuclear explosions have been suggested, among them geothermal heat recovery, oil stimulation, electric power generation, breeding of fissile materials, and energy storage. The absence of detailed studies in these areas, however, leaves their technical and economic feasibility uncertain.

The End of Plowshare

Since the first moratorium on nuclear testing, the United States and the Soviet Union have negotiated several test ban treaties. The Limited Test

Ban Treaty of 1963, ratified by the United States, the Soviet Union, and other countries, prohibits all but underground nuclear testing. The Threshold Test Ban Treaty (1974) and the Peaceful Nuclear Explosions Treaty (1976), signed by both the United States and the Soviet Union, limit weapons tests and peaceful applications to 150 kt for single explosions. Although they still have not been ratified by the Senate, the U.S. is observing the terms of these treaties.

Project Plowshare was terminated in 1977. In the 20 years since its inception,

public anxiety about the health and environmental effects of nuclear technology had mounted steadily. Although studies show that civil nuclear explosions would produce only a few additional millirem of radiation per person per year (a dose equivalent to one round-trip cross-country airplane flight or a week's vacation in the high Sierra Nevada), an influential segment of the public found this unacceptable despite the program's considerable economic promise. In Colorado, for example, legislation now prohibits civil nuclear explosions without prior approval of the electorate.

The application of nuclear energy in any form has become an emotionally charged issue. Together with proliferating legal barriers and waning industrial interest, such concerns were sufficient to end Plowshare. Despite the program's successes, then, this country's use of nuclear explosives for peaceful purposes faces an uncertain future. □

Key Words: Bronco; Buggy; Gasbuggy; Gnome; Hutz; Limited Test Ban Treaty; Plowshare; Rio

Blanco; Ranier; Rufison; Sedan; Threshold; Test Ban Treaty; Trans-Isthmian Canal

Notes and References

1. Unlikely as this statement was at the time, the Soviet Union has conducted many Plowshare-like experiments to date and is currently pursuing a vigorous program of commercial applications.
2. U.S. experience with peaceful nuclear explosives is summarized in L. Ballou, M. Nordyke, and G. Werth, *A Summary of U.S. PNE Experience*, Lawrence Livermore National Laboratory, Rept. UCID-17649 (1977). For a bibliography, see *Plowshare: A Selected, Annotated Bibliography of the Civil, Industrial, and Scientific Uses for Nuclear Explosives*, TID-3522, 9th Revision (1970) and TID 3522-R9-52 (1974); available from National Technical Information Service, Springfield, VA 22151. A more detailed survey of Plowshare (to 1967) may be found in C.R. Corber, R.R. Hamburger, and E.W.S. Hull, *Plowshare*, U.S. Atomic Energy Commission, May 1967 (in the *Understanding the Atom* series). For technical surveys of engineering applications, see *Symposium on Engineering with Nuclear Explosives*, January 14-16, 1970, sponsored by the American Nuclear Society, CONF-700101, Vols. I and II (available from NTIS) and E. Teller, W. Tailey, G. Higgins, and G. Johnson, *Constructive Uses of Nuclear Explosives*, McGraw-Hill, New York (1968).

The Chemistry and Materials Science Department, in support of LLNL's nuclear weapons program, has made numerous technical innovations and has developed many new materials and analysis methods.

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Thirty years ago, LLNL's Chemistry Department (now the Chemistry and Materials Science Department) began its laboratory operations in what had been the ladies' room in the former Bachelor Officers' Quarters of the Livermore Naval Air Station. Since then, both the scope of its work and the size of its quarters have expanded considerably. Over the years, the department's major mission—support of the Laboratory's nuclear weapons program—has involved it in a range of activities remarkable for its variety. For example, we have developed many types of high explosives and new methods for evaluating their performance. We have produced special alloys using exotic materials whose high chemical reactivity and structural instability make them otherwise unusable. Our work with tritium, a radioactive isotope of hydrogen, has deepened our understanding of the chemical and physical properties of this element and its compounds. The hazardous or unusual character of many materials has led us to devise new analytical and diagnostic methods, including computer control of instruments and fast x-ray techniques for examining matter under dynamic compression. We have developed methods for establishing the compatibility of materials in complex systems such as weapons and for predicting and monitoring changes in material properties over time.

A number of technical innovations have emerged from these and other efforts. We review, here, some typical achievements of our work in chemistry and materials science.

Fuel Elements for Pluto

The Laboratory's Pluto program was established in 1957 to demonstrate the feasibility of using a nuclear reactor to propel a supersonic ramjet. A nuclear ramjet is the simplest application of nuclear energy to an airborne power plant. The mission definition for the Pluto program envisioned a vehicle flying at speeds ranging from Mach 3 to 4 at altitudes of 300 to 9000 m and a flight duration of 10 to 24 hours. The nuclear reactor and its associated hard-

ware were able to meet these performance requirements would have to operate continuously at an air pressure of over 2 MPa and at temperatures as high as 1400°C for several hours. These conditions imposed rigorous constraints on our choice of materials.

The Pluto power plant consisted of a single-pass, air-cooled nuclear reactor that served as both a heat source and a heat exchanger. The core of the prototype reactor, the Tory IIA, was designed as a matrix to accommodate about 100 000 individual ceramic fuel elements (Fig. 1). (The core of the "flyable" reactor, the Tory IIC, would contain nearly 300 000 such elements.) The hollow, hexagonal elements contained fissionable material to heat the air flowing through them, which was then exhausted at high temperature and pressure to provide thrust.

The novel technology needed for the reactor materials required a major research effort. In addition to having sufficient structural strength and resistance to moisture and oxidation at high temperatures, the materials would have to be good neutron moderators but poor neutron absorbers. Because the reactor would exchange large quantities of heat with the air at a very high temperature, the materials also would have to conduct heat well to minimize the possibility of mechanical failure from stresses produced by large temperature gradients.

After considerable research that led us to reject a number of candidates, we decided on a fuel element composed of oxides of uranium (enriched in uranium-235), zirconium, and yttrium (to provide chemical stability) homogeneously dispersed in a matrix of beryllium oxide. Equimolar ratios of the ingredients were first mixed and then filtered and dried. The resulting material was blended with organic binders to produce a plastic mass with the proper consistency for extrusion to form the hexagonal elements.

Production-line methods were necessary to fabricate the large number of elements needed. We used a high-pressure ram to extrude the elements, which were then automatically cut to

size, picked up by a conveyer belt, and carried to a 190°C drier. To burn the water and organic binders out of the elements, we heated them in air to 815°C and finally sintered them to their final density in dry hydrogen at about 1650°C for several hours. During

sintering, the elements were confined in special molds to ensure their straightness and dimensional tolerances.

The technology we developed for this process was applied subsequently by the Coors Porcelain Company to produce ceramic components for the

Fig. 1

Single hexagonal fuel element used in the reactor of the Pluto program's nuclear ramjet engine (a), intermediate assembly of fuel elements (b), view of the base plate of the Tory II A reactor before installation of the fuel rods (c), and view of the Tory II A reactor base plate with fuel elements partially installed (d). Air flowing through the

hollow ceramic core of each rod was heated by fissile material in the ceramic matrix and expelled at high temperature and pressure to provide thrust. Significant research in chemistry and materials science was required to develop the innovative materials and techniques used to fabricate the thousands of elements in the operating reactor.

Mode	Quad 1	Quad 2	Quad 3	Results
1	Separated by mass	All masses passed, no gas	All masses passed	Normal mass spectrum
2	Fixed on specific mass	All masses passed, collision gas	Separated by mass	Spectrum of all daughter ions from the selected parent ion
3	Separated by mass	All masses passed, collision gas	Fixed on specific mass	Spectrum of parent ions that fragment to give specific daughter ion
4	Separated by mass	All mass passed, collision gas	Separated by mass	Fixed mass difference between two scanning quads gives specific neutral mass loss
5	Fixed on specific mass	All masses passed, collision gas	Fixed on specific mass	Single or multiple reaction monitoring

Fig. 2

Operating modes of the computer-controlled triple-quadrupole mass spectrometer (TQMS). The basic instrument consists of an ion source, two mass filters, a collision chamber, and a particle multiplier. Operating mode 2 is illustrated below the system schematic. In this mode, a sample is introduced into the ion source, where it is fragmented to form ions. The ions are then separated by mass in the first quadrupole

mass filter. All ions of a particular mass (219 atomic mass units, for example), are directed into the quadrupole collision chamber, where they collide with neutral gas molecules to undergo further fragmentation. The resulting daughter-ion fragments are again separated by mass in the second quadrupole mass filter; these selected fragments then enter a particle multiplier where they are detected.

Tory IIC reactor. Before the Pluto program was cancelled in 1964, both prototype reactors had been successfully ground-tested at the Nevada Test Site (see the article beginning on p. 1).

Computer Control of Chemical Instrumentation

Over the past two decades, the Laboratory has pioneered the application of computer technology to the control of chemical instrumentation. In 1965, the Chemistry Department acquired its first digital computer dedicated to chemistry applications. The PDP-7 was installed in our gas-analysis laboratory. In addition to logging and processing experimental data, the system provided online control of instruments, enabling us to make adjustments during an analysis. Operating in a time-sharing mode, the computer was able to control a variety of experimental equipment simultaneously. By 1971, this included a carbon, hydrogen, and nitrogen (CHN) apparatus, a vacuum-fusion device, a mass spectrometer, an emission spectrograph plate reader, a fluorescence-luminescence spectrometer system, and an automatic sampling atomic absorption system. (The project leader responsible for developing the system received the Sargent-Welsh Chemical Instrumentation Award from the American Chemical Society in 1973.)

One of the first laboratory procedures to be run under computer control was the CHN apparatus, a system for analyzing organic materials for their carbon, hydrogen, and nitrogen content. In this analysis, a sample is oxidized at high temperature to form carbon dioxide, water, and nitrogen. Using selective trapping techniques, the products are then separated and measured. The design of the automated CHN system offered several challenges. As many of the operations involved had not been previously controlled by electrical signals, we had to develop several new devices to integrate the equipment with the computer. Among these were a hermetically sealed, electrically actuated high-vacuum valve and an automated variable-temperature cryogenic

trap. The automated system performed on a level with standard manual analytical procedures, and its novel features are now available on standard commercial instruments.

The success of the computer-controlled gas-analysis system initiated a vigorous program of further computer applications. Our next step was to develop a more advanced computer, the PDP-8/S, into one of the first laboratory-oriented, general-purpose minicomputer systems. Its features included an analogue-to-digital converter, a voltage-to-frequency converter with counter, a programmable clock, multiplexer, disk memory, oscilloscope read-out, and plotter. Many current commercial computer systems incorporate function-control and data-handling systems that are based directly on this pioneering effort.

Our most recent and most advanced computer-controlled instrument is the triple-quadrupole mass spectrometer (TQMS). The TQMS was designed in the 1970s for manual operation. We have now developed a second-generation instrument that is completely computerized, using two LSI-11/23 computers for instrument control and data handling. Capable of operating in five different modes, the TQMS performs mass-spectroscopic analysis of ions previously selected by a conventional quadrupole mass spectrometer (Fig. 2). Depending on the mode the system is set on, the first quadrupole spectrometer (a mass filter) either separates entering ions by mass or selects a particular mass to pass on to the quadrupole collision chamber, where the ion(s) may either collide with a neutral gas to undergo further fragmentation or pass unaltered. The second mass filter acts like the first, separating the ions by mass or selecting a particular mass for measurement in the particle multiplier. The system can operate on either positive or negative ions. The possible combinations of operating modes provide the TQMS with considerable flexibility.

Using the TQMS, we can detect and measure subnanogram quantities of a sample. As a molecular fragment must have both the correct parent mass and

the appropriate fragmentation pattern to be detected, the instrument is highly selective. The low-energy fragmentation process in the collision chamber also makes the TQMS a powerful tool for investigating molecular structure, enabling us to identify all precursor ions of any given ion in the spectrum.

Ensuring Reliability of the Nuclear Stockpile

Our nation's defense posture is crucially dependent on the reliability and safety of its stockpiled nuclear weapons. Though many factors affect weapon reliability, an important one is the time-dependent degradation known as aging. Certain materials used in weapons, such as high explosives and actinide metals, undergo age-related physical and chemical changes that can degrade their functional characteristics.

Fig. 3

Results of an accelerated aging test of three metal coatings on samples of depleted uranium. In this test, the samples were exposed to water vapor and hydrogen gas at 100°C. Accelerated aging tests are an essential step in our evaluation of materials compatibility and prediction of the service life of weapons using such materials.

Electroplated copper

Sputtered copper

Electroplated nickel

To anticipate and monitor such changes, the Laboratory conducts a multifaceted program designed to ensure the continuing integrity of the nuclear stockpile. Activities involving chemistry and materials science begin during the development engineering phase of a weapon system, continue through production, and end only when the weapon has been removed from the stockpile.

Aging of materials can be caused by inherent instability, by chemical reactions with contacting materials, or by responses to mechanical, thermal, electrical, or radiation stress. The effective measurement and prediction of aging effects is based on the idea that the weak links in a weapon system are those materials used in critical components, that is, those that affect functionality. To predict the service life of a weapon, we have established a formal methodology that incorporates this idea. The methodology comprises several steps. First, we obtain data to identify and measure age-related changes in weapon materials. We then analyze the weapon design to determine whether observed changes can affect a critical function. This enables us to establish a failure criterion, a threshold value beyond which functionality is degraded. Using the results of the aging tests, we develop a probabilistic model that describes the observed change in the materials as a function of time. Finally, we apply the model to predict the time to reach the failure criterion.

We evaluate candidate materials for a weapon early in its development engineering by subjecting them to accelerated aging tests. Small samples of a material are tested at elevated temperatures for a day to several months to measure gas evolution (decomposition), weight loss, and chemical reactions with contacting materials (Fig. 3). (Most chemical reaction rates are highly sensitive to temperature, roughly doubling with every 10°C increase.) Accelerated aging temperatures are considerably above those of a service environment. However, the principal failure modes at high thermal stresses are not necessarily dominant at the lower stresses

typical of service conditions. We take this into account by conducting longer term aging studies at moderate stress accelerations during the next stage.

Materials that pass the initial screening are subjected to accelerated core tests, in which they are assembled into configurations that model the material interfaces in the weapon design (Fig. 4). These tests, which are carried out at temperatures appropriate to service conditions and may last from months to several years, are intended to provide more realistic data on the interaction of materials and components in the system. The core tests also enable us to define a temperature acceleration factor for any change that might affect functionality. This factor is used in our probabilistic model to predict the time it will take the materials to reach the failure criterion.

Our testing activities continue after a weapon has completed development engineering and entered production. To determine quickly whether components retain their properties in a real weapon system, and to provide a baseline for evaluating subsequent surveillance observations, we randomly select a weapon from the production line early in the production stage. This enables us to inspect, for the first time, a fully assembled weapon, including all materials, components, and interfaces. The weapon is subjected to accelerated aging tests designed to reveal any problems that might require immediate corrective action. Although specific testing strategies vary with the particular system, they usually entail exposure to elevated temperatures. In addition to accelerating material changes, such tests may also induce previously undetected mechanical stresses.

Finally, we continue to monitor weapon reliability and check the validity of our predictive models by periodically removing a randomly selected weapon from the stockpile for inspection (Fig. 5). Bolstered by many years of experience and analysis in chemistry and materials science, the Laboratory's ongoing stockpile reliability program helps to ensure that our nation's deterrent remains both effective and safe. ■

Fig. 4

Weapon materials before assembly for an accelerated core test. The material interfaces in the test core reproduce those of an actual design but have a simplified geometry; the assembled configuration is cylindrical. This type of test is designed to study possible effects among the weapon materials. Shown here are several types of metallic parts together with a number of plastic and organic components.

Fig. 5

New bridgewire (a) and corroded bridgewire (b). Once the corrosion was discovered, testing was done to determine how well the detonators perform in spite of the corrosion; tests showed that corroded detonators perform to specification. Such monitoring is essential for ensuring the reliability of weapons in the national stockpile.

Key Words: accelerated aging; carbon-hydrogen-nitrogen (CHN) apparatus; nuclear stockpile; Pluto; Tory IIA; Tory IIC; triple-quadrupole mass spectrometer (TQMS).

Computing at

LLNL

The modern electronic digital computer, which predates the Laboratory by only a few years, has become in the last three decades as common a utility as telephones and electricity.

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Throughout its three decades of existence, the Laboratory has demonstrated strong leadership in the field of computing. This leadership falls into three major areas:

- Encouraging the development of ever more powerful computing hardware by contracting for and using the most advanced machines available in each generation of computers.
- Devising computational techniques and applying them to a variety of scientific disciplines.
- Designing and implementing new computer systems that have included the most innovative concepts of their time, such as high-level languages, interactive time-sharing, networking, and graphical output.

Hardware

One can trace the history of automated computation through the development of such devices as stones and rods, the abacus, mechanical clocks and orreries, the Jacquard loom, the slide rule, the desk calculator, Charles Babbage's Analytical Engine, and the machine of Alan Turing. However, the electronic digital computer as we know it today predates the Laboratory by only a few years, having appeared just after World War II. The first commercial

computer produced in quantity, the Univac I, had been in service for only two years when one was installed at Livermore in April 1953, when the Laboratory was only seven months old (Fig. 1). The Livermore machine, serial #5, was the identical one that had received national attention the preceding November when it appeared on television predicting President Eisenhower's election victory over Adlai Stevenson. At the time of the election, Laboratory personnel, fresh from a crash course in the new art of computer programming, had been working with the machine for a couple of months at the vendor's facilities in Philadelphia, where they would continue to work until the machine was shipped to Livermore. Meanwhile, in Livermore, other programmers struggled along with the Laboratory's first computers, two IBM card-programmed calculators (CPCs).

Someone (who would rather not be named) had predicted that about a dozen Univacs would be sufficient to solve all the problems in the world. However, at Livermore it was clear from the beginning that Univacs would not be adequate for the Laboratory's needs, not to mention those of the whole world, and even today, after 30 years, we are a long way from having all the computational power we could use.

One might have expected that the arrival in early 1954 of the IBM 701, twelve times faster than the Univac, would have reduced the time needed for nuclear explosives computations from the 100 hours they had been running to about eight hours. Instead, the 100-hour runs continued, although the programs gave improved results because of finer resolution and more detailed physics. Over the years, increased speed eventually did have an effect on running time. Today, typical nuclear explosive computations require an average of about five hours, although 60 hours is not unusual.

The Laboratory did not simply wait for newer, faster, and larger computers to appear in the marketplace; it contacted the manufacturers and urged them to design for our needs. The IBM

Fig. 1

The Univac I computer, installed at the Laboratory in April 1953.

704 and its successor the 709 (with built-in floating point and magnetic core memory, 8000—eventually 32 000—words of it) were developed in part because of our encouragement, and they carried us almost to the end of our first decade (Fig. 2). Our next machines, the Remington Rand LARC (Livermore Advanced Research Computer) and the IBM 7030 (more commonly known as Stretch), were commercial failures (only two of the former and eight of the latter were ever built), but they served the Laboratory long and well, nearly a decade each (Fig. 2). Our experience with Stretch was a great help to IBM in designing its first commercially successful transistorized computers, the 7090 and 7094 (Fig. 2). Both of these were used at the Laboratory, the last of them leaving in 1972.

As the Laboratory entered its second decade, in the early 1960s, a change began to occur in its relationship with the computer industry. The most powerful machines being produced still did not completely fulfill the Laboratory's needs, but they were becoming more than adequate for most buyers of computers—business and financial institutions. Gradually, the Laboratory found itself one of a relatively few customers in a specialized large-computer market. Most manufacturers dropped out of that market, concentrating on the much higher volume markets for small and medium computers. For more than 15 years, all of our new computers came from one source, the Control Data Corporation (CDC), the 1604 and 3600 in 1963, the 6600 beginning in 1964, and the 7600 beginning in 1969. During 1974, we had two 6600s and four 7600s, and today we still have four 7600s (Fig. 3).

In the early 1970s, it became clear that a technological plateau had been reached. The huge increases in speed of the preceding decades (by a factor of about 10 000 from the Univac I to the CDC 7600) could no longer be obtained following the same approach. Taking a new direction, the Laboratory encouraged the development of explicitly parallel machines, in which many closely coupled processors work on a single

Fig. 2

Computers used at the Laboratory in its first two decades: top, IBM 704; middle, LARC; bottom, IBM 7094.

Fig. 3 The CDC 7600 computer, still in use at the Laboratory.

Fig. 4 The Cray 1 computer, a pipelined vector machine in current use at the Laboratory.

problem simultaneously. After a rather complex history, these efforts eventually led to the development of the Illiac IV, which was installed at the National Aeronautics and Space Administration's Ames facility. Although the Laboratory made some use of that machine, we are today still looking forward to having our own parallel processing computer, perhaps the one from CDC or Cray Research.

The next generation of computers the Laboratory consisted not of explicitly parallel machines but of pipelined vector machines, in which a single instruction can induce a long sequence of rapidly executed instances of the same operation. The first such machines were the CDC Stars that were installed in late 1974. These were followed by the Cray 1, beginning in early 1979 (Fig. 4). Among our current major computers are about a half dozen of the Crays, and these are supplemented by the CDC 7600s.

The appearance in the marketplace of Cray Research, manufacturer of the Cray 1, restored competition to the large-computer market. Both Cray and CDC are now working on more advanced designs, and there is a possibility that other manufacturers will join them. The Laboratory expects to install and use these new computers as rapidly as they become available. Figure 5 summarizes graphically the history of large computers at the Laboratory.

Fascination with the enormous power of processors like the Cray 1 should not blind us to the critical importance of other computational facilities: storage, input-output, and communication. The Laboratory has found it necessary to encourage development of these facilities, as it did the mainframe processors, and to acquire the biggest and best of each generation. We can mention here only a few highlights.

Unquestionably, the premier storage highlight was the IBM photodigital store, which was with us for more than a decade beginning in the late 1960s. It was the first trillion-bit device and a fantastic sight to watch in operation (see box on p. 35). We would still be using it today if its parts had not

become too outdated to be maintained. In many respects, it has not been equalled by today's trillion-bit devices, the Automated Tape Library and the CDC 38500.

Almost as interesting to observe in action as the photostore was the one-of-a-kind Radiation, Inc., high-speed

printer, which served us from the mid-1960s to the mid-1970s (Fig. 6). This printed at a rate of 30,000 line/min, generating about 10 million pages per month. The printed quality was poor (black on a gray, often foul-smelling paper), but it did the job. When the printer finally wore out, nothing as fast

Fig. 5

History of large computers at the Lawrence Livermore National Laboratory.

Fig. 6

The Radiation Inc., printer used from the mid-1960s to the mid-1970s.

was available to replace it, so two 18 000-line/min Honeywell printers were acquired, and these produced a far more pleasing black on white, odor-free format. In recent years, with the use of FR 80 and Dicomed recorders, much of our output has been on film and fiche, rather than paper. The output from these recorders consists of pictures and text, and a significant portion is in color and is of photographic quality.

Acquiring the best of each kind of equipment has meant that we deal with several manufacturers at a time. When two pieces of equipment of different manufacture must be connected, not always is one manufacturer or the other willing to supply the required interface. Therefore, the Computation Engineering Group in the Laboratory's Electronics Engineering Department often has been called upon to build such interfaces and to construct other devices that are not available in the marketplace.

Over the years, these engineers have designed and built many devices that were beyond the then-current capabilities of commercial vendors: multiplexors for interactive terminals and remote computers, a vector-generator/scan-converter for the Honeywell printers,

memory interfaces for the PDP-10, a crossbar switch for the Television Monitor Display System (TMLD), almost the entire system to support the CDC 38500, and many more. A recent development that has reduced but by no means eliminated the need for Laboratory built intercomputer communication interfaces is the Network Systems Corporation Hyperchannel, which can interconnect a wide variety of computers and other devices by means of a shared high-speed "bus" (which has a capacity of 50 million bit/s).

The Laboratory is a difficult customer for computer manufacturers to deal with because the size of the computations we perform makes it necessary for us to use our equipment right up to its limits. For example, in the early days of our use of the CDC 38500 storage device, we had a very high rate of mechanical failures, with the cartridge tapes jamming or slipping out of place. When we were told that another installation was not having such problems, we went to investigate. We learned that they made only about 200 storage accesses per day, while we were driving the device at its capacity of an access every few seconds. It would take them nearly a year to use the device as much as we did in one day.

Applications

Why does the Laboratory need frequent storage access, large storage capacity, rapid processing, high bandwidth communication, and copious output? Most of the need arises from the demands of the nuclear explosives program, and it is these demands that have driven the Laboratory to the forefront of the computing field. Even before the Laboratory first opened its doors in Livermore, it was clear that computers would be essential to the nuclear design effort, and the Univac I had already been ordered.

Our scientists immediately began to develop appropriate programs, using finite differences, Monte Carlo, and other numerical techniques to simulate the complex physical processes that take place within nuclear devices. These programs grew steadily as the

The IBM Photodigital Store

The IBM Photodigital Store was the first trillion-bit device. Those of us who first saw this Rube Goldberg invention at the testing facility in San Jose had to struggle to keep straight faces, but, incredibly, it worked and worked well, eventually recording several trillion bits (all but one trillion of which were, at any one time, stored outside the machine on shelves). The storage medium was high-density silver halide photographic film in the form of small 3-by-6-cm chips, 32 of which were stored in a plastic box or cell. New cells inserted into the device were automatically opened, and a picker transferred the fresh chips one by one into a high vacuum, where they were

outgassed and then written on with an electron beam. The electron gun would automatically refocus itself between chips and periodically changed its own filaments from a two-week supply. After being written, each chip went through a 3-min development sequence involving automatic application of photographic chemicals, wash water, and dry air. The developed chips were transferred into waiting cells and blown through pneumatic tubes to storage racks, from which they could be pneumatically fetched to reading stations and read with a flying optical spot. Elaborate redundancy in the recording process enabled the reader to detect and correct errors (arising from film flaws) in as many as 10% of the recorded bits. The whole device, nearly 10 m long, was managed by a built-in computer that operated all the switches, valves, motors, beams, lights, and doors.

years went by, accumulating within them more and more detailed and precise physical descriptions. The codes were moved from machine to machine as new computers arrived. They came to be supported by additional programs that prepared their input, edited their output, and converted that output into pictures and graphs. They became interactive so that they could be examined and adjusted in the midst of a problem run; in particular, "rezoners" enabled physicists sitting at television screens to correct overly distorted finite-difference meshes. Today, nuclear applications routines consist of great families of related programs, each with an unbroken history extending back for many years, in some cases to the very first days of the Laboratory.

All this activity has made the Laboratory a leader in the disciplines of numerical computation. The sheer size of our computations has forced us to search for and discover the most efficient programming and computing techniques and to identify the limitations of those techniques. We have investigated methodologies for explicitly parallel machines, even though we have not yet acquired one. With the acquisition of the CDC Stars, we became the first user to learn what was really involved in the efficient use of pipelined vector machines.

Our great computational capacity, although developed primarily because of the needs of the nuclear explosives program, has been put to many other uses. In some cases, these other uses have drawn heavily upon what had been learned in programming nuclear explosives problems. For example, since, in many respects, a star is just an enormous fusion device, the Laboratory has been able to make significant contributions to astrophysics with its numerical studies of stellar evolution. In other cases, only the numerical methods, not the subject matter, resemble nuclear computations; an example is our work on a model of the atmosphere that involved more than 14 000 dependent variables.

In still other cases, the programs used are completely different from

nuclear explosives efforts. Some computer programs that have attracted widespread public interest are, in fact, quite peripheral to major Laboratory activities. One such is a celestial mechanics program of very high precision that has yielded the best information available about the return of Halley's comet (next due on February 9, 1986). The same program has revealed discrepancies in celestial motions that suggest the possibility of a tenth planet, beyond the orbit of Pluto. Another program of general interest is the one that discovered the largest prime number yet identified: $2^{4497} - 1$; if written out in full, this number has 13395 decimal digits.

Systems

A great deal more could be said about application programming at the Laboratory, the disciplines involved, and the advances made. Leaving that discussion, however, to the historians of the various fields of application, we turn now to systems programming. The distinction between systems and applications, which today is so familiar, was not always made. It evolved gradually and was not formalized in the organization of the Computation Department until the early 1960s. Prior to that, one's place in the organization was based primarily on the kind of computer one used, not on what one did with it.

The earliest machines were operated hands-on and really had no operating systems. Systems work consisted in writing, or in modifying and maintaining, assemblers, loaders, and input-output routines. Then, we entered the world of batch processing, and the primitive operating systems required were supplied by the vendor. This situation changed with the arrival of the LARC and Stretch. Unlike their predecessors, which relied almost entirely on tape for secondary storage, these machines had drums and disks, and a more sophisticated operating system was required. The vendors did not supply such systems, so they were designed and written by Laboratory personnel.

Another important systems effort during this period related to the first high-level programming language, Fortran. The Laboratory had been represented on the team that designed this new language and had immediately put it to use, although assembly language continued to be used (as it is today) when the greatest efficiency was required, as in the critical inner loops of large programs. Originally, Fortran was used only in applications, for which it had been designed. However, Laboratory programmers soon enhanced the language and its compiler to provide features valued by systems programmers, yielding a new super-Fortran called LRLtran (after an acronym for one of the Laboratory's early names). Then, in a revolutionary *tour de force*, they rewrote the compiler in this new language, giving us a compiler that could (and did) compile itself. Next, upon the arrival of the CDC 3600, they wrote the bulk of an entire system in LRLtran.

The next step was an even bigger one. The Laboratory became aware of a new idea, called time sharing, that would replace batch processing just as that had replaced hands-on operations. Time sharing restores most of the convenience and intimacy of the hands-on era, since the user interacts directly with the computer through a keyboard terminal; yet, the computer does not sit idle during the user's thinking time. Because the CDC 6600s, which were arriving at about this time (the early 1960s), had no vendor-supplied system whatsoever, we had to write our own system. The modern time-sharing system we wrote evolved into what came to be known as the Livermore Time-Sharing System (LTSS). The LTSS later was moved to our 7600s, Stars, and Cray 1s, giving it a lifespan of at least two decades.

The advent of interactive time sharing at the Laboratory was closely associated with another development—networking. The combination of the two yielded a unique computing environment that has been duplicated at only one other place on anywhere near the same scale, at our sister laboratory

in Los Alamos (which has used some of our software, such as LTSS, just as we have, from time to time, been assisted by them). Networking originally was motivated by two things. First of all, certain activities, such as the character-by-character operation of interactive terminals, placed a significant load on the time-sharing systems, reducing the time they could devote to running the users' programs. We decided to offload such activities onto other, smaller machines which then, of course, had to be connected to the large machines. Secondly, it was necessary to share facilities among computers, and this required that they be interconnected; for example, the usefulness of the photostore was increased many fold because the files that it stored could be accessed from all the major computers.

The notion of networking evolved gradually. We did not decide to build a network; we simply started to provide for offloading tasks from the major computers and for resource sharing. Gradually, we came to realize that we were building a very flexible web of interacting computers, each doing the particular activities for which it is best suited. New facilities could be added with relative ease and minimal disruption. So, for about 15 years we have had a local network, called Octopus, that is more general and more capable than most of the local networks that are being planned today (Fig. 7). The Octopus networking experience was invaluable when the Laboratory was chosen as the central site for a national computer network, the magnetic fusion energy network.

The Octopus network has provided a framework in which a wide variety of new and useful system concepts and facilities have been implemented. For example, we read the papers from the Multics project at the Massachusetts Institute of Technology describing the naming of files and other resources using graph-structured directories. We then put the idea into practice in an even more thoroughgoing way. With the introduction of the TMDS, we provided for rapid display of both text and pictures on television monitors next to

Fig. 7 The Octopus network.

the users' terminals. We have extended the offloading of tasks onto smaller computers by introducing microcomputers; for example, character-by-character keystroke interaction with keyboard terminals is now handled by a microcomputer on each terminal line.

Some of the most exciting developments have been in the area of computer graphics, where sophisticated software has been combined with high-quality output devices to produce a wide variety of visually exciting images that enable the scientist to comprehend

more fully the results of his computations. The images produced can involve motion as well as still pictures, color as well as black and white, shading and gray-scale as well as two-tone, and holograms as well as two-dimensional pictures (Fig. 8).

We have come a long way from the CPCs and Univac I of 30 years ago. Then, using a computer was a major undertaking, something that one would plan for all day, lest one fail to use to the fullest every second of one's brief turn at the console. Today, computers

Fig. 8

Example of computer graphics: computer drawing of a double helix of 20 base pairs of DNA.

are as common as telephones and electricity, something that is available right in one's office whenever one needs it. Without the convenience of access to an interactive computer network, professional productivity at the Laboratory would be several times lower. However, the current situation does not represent the ultimate in computer system organization, and the next step already is being taken. The rapidly decreasing price of micro- and minicomputers means that soon most offices will contain not only an interactive keyboard terminal but also a small computer that will carry out one's smaller computations right at one's desk and form the portal through which one can access the larger processors and other facilities

of the network. Our systems programmers are now developing a software framework for this more widely distributed environment—the Livermore Interactive Network Communication Standard (LINCS). We expect the evolution of the last 30 years to continue.

Key Words: computer—CDC (3600, 6600, 7600, 38500, Star), Cray 1, IBM (701, 704, 709, 7030, 7090, 7094), Illiac IV, LARC, Univac; computer graphics: Control Data Corporation; Ray Research; explicitly parallel machines; Fortran; Livermore Time-Sharing System; LRLtran; TSS; Network Systems Corporation Hyperchannel; network; numerical computation; Octopus; photodigital store; pipelined vector machines; Radiation, Inc., Remington Rand Livermore Advanced Research Computer; Stretch; systems programming; Television Monitor Display System; time sharing; TMD5.

An Acknowledgment

So many persons have contributed in so many ways to the development of the Laboratory's computing capability that to select any of them for special mention would be unfair to those who could not be credited for lack of space. There is one exception: Sidney Fernbach pioneered computing at the Laboratory and headed the Computation Department for more than 20 years. His contributions and influence are unique and pervasive. Without him, it is doubtful that our computing history could have been even approximately the same.

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