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Frank A. Morrison, Jr.

1943 - 1984

Frank A. Morrison, Jr., Scientific Editor since November 1983 of the Laboratory's companion technical journals, *Energy and Technology Review* and *Research Monthly*, died from injuries suffered in an automobile accident on August 1, 1984. A specialist in heat transfer and fluid dynamics, he joined the LLNL staff in 1977 after serving for several years as a consultant to the Laboratory. He came to Livermore from the University of Illinois, where he had been on the faculty of the Department of Mechanical and Industrial Engineering and had served as Assistant Dean of the School of Engineering. Just before coming to Livermore, he was promoted to full professor, the youngest full professor in the history of the department. His honors while at the University of Illinois included the Special Undergraduate Instruction Award, the Effective College Teaching Award, and selection in 1977 as the Outstanding Young College Educator by the Champaign-Urbana Jaycees.

He received his undergraduate and graduate degrees from Carnegie-Mellon University in Pittsburgh, Pennsylvania, earning his Ph.D. in 1966, and did postdoctoral work that included a year at the University of Cambridge, England, on a National Science Foundation fellowship.

He was a member of the American Society of Mechanical Engineers, the American Association for the Advancement of Science, and the Society for Petroleum Engineers. He served as a panelist for the National Research Council and as reviewer for several professional journals.

After two years at LLNL, Frank was named the Section Leader for Geomechanics in the Earth Sciences Department. Three years later, in 1982, he was selected to lead the Nuclear Test Program's Underground Containment Program. In November 1983, the Laboratory chose Frank as the Scientific Editor of the *Energy and Technology Review* and the *Research Monthly*, an assignment made as much for its broadening experience as for its immediate demands. He assumed these editing responsibilities in addition to those of program leader.

Frank contributed much to the scientific programs of the Laboratory, most recently by developing new and vastly improved techniques for assuring the underground containment of nuclear tests and by advancing our understanding of containment phenomenology. As editor, Frank displayed the enthusiasm, breadth of scientific interest, and attention to detail that characterized all of his work at the Laboratory.

Frank also brought much to his colleagues, both in scientific brilliance and in personal style. Much of what Frank has done and the manner in which he did it will become the standards against which many of us will measure our own performance. Frank was a creative and motivating spirit with a perpetual twinkle in his eye. He will be greatly missed.

Earthquake Safety at LLNL

Motivated, at least in part, by direct and recent experience with earthquakes, we have greatly improved the seismic safety of the Laboratory.

On the morning of January 24, 1980, four earthquakes with Richter magnitudes of 5.9, 5.1, 4.0, and 4.8 struck the Livermore Valley within about three minutes of one another from epicenters about 20 km northwest of the Laboratory. Two days later, there was another temblor of magnitude 5.4; this time, the epicenter was only 6 km northwest of LLNL, but it did relatively little damage at the Laboratory. The earthquake intensity was VII to VIII on the modified Mercalli index (see the box on p. 4). Peak ground accelerations experienced at the Laboratory during these earthquakes were estimated to be in the range of 2 to 3 m/s² (0.2 to 0.3 g), mostly in the east-west direction.

Although no one at the Laboratory was seriously injured, these earthquakes caused considerable damage and disruption (Fig. 1). Masonry and concrete structures throughout the Laboratory cracked and broke. Connections between tilt-up concrete walls and their supporting structural steel frames parted. A few structural steel framing members in some of the buildings buckled. Some trailers used as temporary office space were inadequately anchored and fell off their pedestals. The book stacks in our main library collapsed (see the box on p. 8).

Jars and bottles were thrown from storage shelves in many chemistry laboratories, forming pools of mixed

chemicals on the floors. In one of the engineering office buildings, most of the ceiling tiles, overhead light fixtures, and air diffusers fell to the floor. Overturned bookcases, storage shelves, and filing cabinets were commonplace. Many building elevators could not be used because their counterweights had been knocked loose, bending their guide rails.

There was surprisingly little damage to the Laboratory's utility systems. We lost power for a while, causing the main computers to shut down and security booths to lock closed, which impeded access to some areas. Water leaks occurred in some of the mains and building systems, although the main water supply to the Laboratory was undamaged and water for fire fighting was available at all times. The few natural gas leaks in the mains and building systems were all minor. Our supply of propane, held as an emergency replacement for natural gas, was undamaged.

The structures that house the Laboratory's supply of nuclear materials sustained no damage. They and their associated safety systems performed as expected.

Immediately after the earthquake, the Medical Department received about 35 patients, none of whom required ambulance transfer. During the following weeks, about 30 more individuals reported injuries apparently related to

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Fig. 1 Scenes of destruction on January 20, 1980. (a) Toppled shelving in the main library stacks. (b) Stairs that had to be pulled away to free the occupants of a trailer dislodged from its support pedestals. (c) Bookshelf toppled onto a desk. (d) Desk covered with lighting fixtures and broken false-ceiling tiles. (e) Mixed chemicals spilled from shelves. (f) Fluorescent lighting fixture that fell from the ceiling onto a drafting table.

the earthquakes. Of the 65 injuries, which included lacerations, sprains, bruises, back problems, and other minor conditions, more than two-thirds were caused by falls or falling objects.

Earthquake Clean-Up and Restoration Efforts

These moderate earthquakes showed us, at first hand, the disruption, damage, and pain, both emotional and physical, that could be caused by a natural disaster. We came out of this experience with an awareness we had lacked before.

As a result, we initiated an intensive, Laboratory-wide program both to repair earthquake-damaged facilities and to protect our many employees and the surrounding community from the potentially hazardous side effects of future earthquakes.^{1,2} Basically, the work entailed:

- Immediate repair and clean-up for the resumption of Laboratory operations.
- Repair of damaged structures and facilities.
- Improvement of disaster response and evacuation capabilities.
- Strengthening of structures, utilities, and individual work stations to improve safety.
- Reduction of personnel risks and secondary damage potential from natural gas, fire, flooding, contamination, and other hazards.

Over a period of three to four years, we spent about \$10 million for earthquake-related repairs and structural improvement.

Our immediate task was to restore normal operation by repairing the Laboratory's damaged facilities. Paramount in everyone's thoughts were safety issues, given urgency by the imminent possibility of further ground shaking. To address these earthquake-related issues, we assembled a structural engineering group drawn from Laboratory personnel with experience in supplying structural design support to major laboratory projects. We also engaged an independent structural-engineering firm specializing in the abatement of seismic hazards to review our findings and to evaluate our proposed measures.

On surveying the Laboratory, we found that much of the damage and disarray was superficial. Although many of the concrete buildings had experienced various degrees of cracking, most of them were still safe for occupancy. Nevertheless, concrete cracks raise at least psychological safety concerns, and, in the long term, water tightness is important to protect the reinforcing steel. We therefore repaired the concrete walls by injecting high-strength epoxy, a system in use worldwide to repair damaged concrete structures.

The basic process is to seal off the cracked concrete surface with a thermoplastic membrane, leaving several small holes for the subsequent injection and relief of the structural adhesive. After the surface seals cured, crews worked their way along the cracks, injecting the epoxy adhesive until it oozed out farther along, gradually filling all of the cracks (Fig. 2). (The epoxy adhesive will penetrate cracks in concrete as narrow as 50 μm .) After curing at ambient temperature, the epoxy-filled cracks are much stronger than the parent concrete. This process restores the concrete structure to near design strength.

Almost immediately after the 1980 earthquake, we began tying down office equipment and major shelving (filing

Fig. 2

Crew repairing cracked concrete with epoxy adhesive. The adhesive is pumped into the cracks at intervals until it extrudes farther along the crack through a hole in the thermoplastic surface seal. After curing, the bond is stronger than the parent concrete; this repair restores the concrete structure to near design strength.

cabinets, bookcases, etc.). We now require that all bookcases more than 1.2 m tall be anchored. We specified that the new library shelving be able to withstand a peak acceleration of 5 m/s^2 .

We surveyed all our buildings to define the magnitude of the required tie-down effort. Considering the number of

buildings, trailers, and people involved, the tie-down of office equipment quickly became a major effort. We engaged outside contractors to anchor our office equipment systematically, one building at a time.

Because of a chronic shortage of office space at the Laboratory, many people are

Earthquake Intensity

Earthquakes come in all sizes, from the unnoticeably small and frequent to the disastrous but fortunately rare. The Mercalli earthquake intensity index (as modified in 1958 by Charles F. Richter) is based on effects noted at a particular site (as distinct from earthquake magnitude, which is related to intensity at the epicenter.) It enables us to compare present and historical earthquakes, including those whose epicenters are poorly defined. Its different levels, denoted by Roman numerals, are as follows:

I. Not felt. Noticed only by marginal and long-period effects.

II. Felt only by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks or sensation of a jolt like a heavy ball striking the walls. Standing motor vehicles rock. Windows, dishes, and doors rattle, glasses clink, crockery clashes. In the upper range of IV, wooden walls and frame creak.

V. Felt outdoors. Direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters and pictures move, pendulum clocks stop, start, or change rate.

VI. Felt by all. Many people frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks and books knocked off shelves, pictures knocked off walls, furniture moved or overturned. Weak plaster and masonry D (made of weak materials such as adobe and poor mortar, with low standards of workmanship and scant horizontal strength) cracked. Small bells (church, school) ring. Trees and bushes shaken (visibly, or heard to rustle).

VII. Difficult to stand. Noticed by drivers of motor vehicles. Hanging objects quiver, furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose

bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C (of ordinary materials and workmanship, with no extreme weaknesses like failure to tie in at corners but neither reinforced nor designed against horizontal forces). Waves on ponds, water turbid with mud. Small slides and cave-ins along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor vehicles affected. Damage to masonry C; partial collapse. Some damage to masonry B (good materials and workmanship, reinforced but not designed in detail to resist lateral forces); none to masonry A (good materials, workmanship, and design; reinforced, especially laterally, and bound together with steel or concrete to resist lateral forces). Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed pilings broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed and masonry C heavily damaged, sometimes with complete collapse. Masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted down, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. Sand craters, earthquake fountains, and sand and mud ejected in alluvial deposits.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, and embankments. Large landslides. Water thrown on banks of canals, rivers, lakes. Sand and mud shifted horizontally on beaches and flat land. Railroad tracks bent slightly.

XI. Railroad tracks bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

housed in trailers, and many of these were inadequately anchored and suffered earthquake damage. Since 1980, all of our new trailers must meet the design requirements of the latest Uniform Building Code (issued every three years, most recently in 1982) and must also resist concurrent lateral and vertical ground accelerations of 2.5 and 1.67 m/s², respectively. Measures to prevent new and existing trailers from falling or overturning in a large earthquake include piers with soil anchors (Fig. 3), cribbing that allows sliding, and perimeter foundations with anchors.

Following the 1980 earthquake, we upgraded all ceilings and light fixtures to comply with the current edition of the Uniform Building Code. In addition, we upgraded the ceiling systems that had been simply hanging, adding vertical struts to enable them to resist vertical seismic forces acting either upward or downward. We also secured the plastic lenses used with ceiling lights so they would not come loose and fall.

The Laboratory has about 54 bridge cranes in its various shops and experiment buildings. Although none of the trolley/bridge assemblies of these cranes jumped off their rails and fell during the 1980 earthquake, the results of such an accident could be serious. We therefore decided to install mechanical restraints to prevent these assemblies from leaving the crane rails in the event of an earthquake.

Rigid connections between tanks and piping headers are vulnerable to rupture during earthquakes because the tanks and piping systems are independently anchored. Any significant differential movement could break the piping near tank connections. Although the piping on our propane tanks survived the 1980 earthquakes without damage, we are installing flexible piping connections to prevent future failures. We are also installing automatic gas shutoff valves, activated by earthquake motion, to help prevent fires or explosions due to gas leakage.

Although our computer facilities came through the 1980 earthquakes relatively unscathed, the damage could have been serious if the earthquake had been more

severe. Computer equipment worth millions of dollars rests on suspended flooring (as much as 60 cm above the subflooring) for ease in routing plumbing, electrical conduits, and forced-air ducts. In our survey of seismic hazards, we devoted a great deal of attention to the design of computer-room flooring.

Computer-room floors typically rest on vertical supports made from thin-walled (1.5-mm-thick) steel tubing (25 mm in diameter) welded to steel base plates, distributed 60 cm apart in a rectangular grid pattern and glued to a concrete subfloor. Small beams known as stringers, often fastened to the tops of the pedestals with only small screws, support the floor panels both vertically and horizontally. Knee bracing of the pedestals for lateral support often is omitted because it obstructs the passage of electrical conduit, piping, and ducting beneath the floor.

Since many of the original pedestals lacked knee bracing, their only resistance to sideways forces was provided by the bending stiffness of their pedestal tube. This raised questions about whether the base plates and pedestal tubes were thick enough and about the reliability of the glue joints and the base-plate welds.

We decided to strengthen the existing computer-room floors and to ensure the

Fig. 3

Soil anchors to hold temporary office trailers on their support pedestals and prevent them from tipping over. Other trailers have been upgraded with platform supports that enable them to slide without falling.

earthquake resistance of new ones (Fig. 4). Accordingly, we have prepared new standards, specifications, and drawings that encompass all seismic aspects of computer-room floor design. We now require all suppliers and

Fig. 4 ▲

Raised computer-room flooring, which allows easy access and freedom of routing for multiple layers of pipes, ducts, and cables. None of these floors failed during our 1980 earthquake, but damage would have been severe and losses expensive if they had. We have now installed diagonal braces, such as those shown here, for added stability against horizontal stresses.

Fig. 5 ▼

Buttresses added to stiffen Building 311, a two-story office structure damaged in the 1980 earthquake. The buttresses are much stiffer than the building, in effect extending the ground up around it. They distribute lateral forces to the roof and the second-story floor, greatly relieving bending forces on the building's original columns.

vendors of raised computer-room floors either to use our standard drawing for pedestal assemblies or to demonstrate by tests or calculations that their pedestals and floor panels can meet our seismic criteria.

Seismic Upgrade of Buildings

Two of our reinforced concrete buildings (buildings 311 and 113), built to 1961 standards, were exposed in the 1980 earthquakes to seismic forces about four times those specified in the original building design and suffered considerable structural damage. In Building 311, a two-story office building with about 3500 m² of floor space, there was extensive cracking of external support columns. In the main part of Building 113, a five-story reinforced concrete structure with about 4000 m² of office space, there was considerable cracking of interior shear walls.

Building 311 was designed to resist a lateral force of 6.7% of its own weight; for Building 113, the corresponding figure was 5.7%. The 1982 edition of the Uniform Building Code raised these requirements to 9.4% and 14%, respectively, still only about one-half the stress experienced from the peak acceleration of 2.5 m/s² in our 1980 earthquake. We decided to go far beyond the code requirements and design for a peak ground acceleration of 5 m/s².

After considering many alternative upgrading schemes, we decided to brace Building 311 with external buttresses to relieve the external columns from carrying so much of the earthquake stress (Fig. 5). These buttresses are many times stiffer than the existing concrete frame of the building; their effect is to distribute the earthquake ground motion, applying it to the building by pushing and pulling on the second floor and the roof. Hence, the building columns, which were originally designed to resist ground motion all by themselves, will be subject to very little of the seismic forces.³

The five-story tower on Building 113 was too tall to brace with buttresses. Instead, we stiffened it with K-braced frames (similar to bridge trusses) made of high-strength rectangular steel tubing.

Individual sections of this frame were assembled at the site and welded in place around the building perimeter (Fig. 6a). The frames were then attached with grout to the outside face of the building perimeter and to the existing foundation system. Figure 6b shows the completed upgrade.

The cost and time for the structural upgrade was about \$1.5 million (1982 dollars) and 10 months for Building 311 and about \$1.1 million and 9 months for Building 113. Replacement of the two buildings would have taken much longer and would have cost about \$4.6 million and \$5.9 million, respectively. In addition, because almost all of the structural work on Building 113 took place on the outside, it was possible to reoccupy the building shortly after the earthquake and to continue to use it throughout the erection and installation of the external frame.

We are also evaluating a proposed seismic upgrading of Building 111.

Building 111 was designed in accordance with the 1964 Uniform Building Code. It is built of reinforced concrete and consists of three 7-story wings and one 5-story wing joined at a central core. Building 111 suffered some cracking of internal shear walls in the 1980 earthquakes. Seismic review revealed that the building has some structural deficiencies, and some of these are being corrected. Additional grade beams will be installed in the building's foundation system, and a few window openings at the second-floor level will be filled with reinforced concrete. These changes have increased the building's seismic safety, and further seismic upgrades are being considered.

Livermore Site Geologic and Seismologic Studies

Since early 1979, we have been engaged in comprehensive geologic and seismologic studies of the LLNL site and its surroundings to evaluate potential geologic hazards that could adversely affect the safety of our operations. The 1980 earthquakes added impetus to this research.

To better understand the local seismic activity, we studied the geology of the

region and reports of earthquakes dating back to the mid-1800s. The substratum beneath us consists of continuous sedimentary layers as much as 1200 m thick and dates from geologically recent times to several million years old. No active fault offsets cross the site, making surface rupture very unlikely (see the article on p. 10 of this issue).

Historical earthquake information turned out to be useful but incomplete. For example, it proved impossible to

Fig. 6

Upgrading the five-story office tower of Building 113. (a) Welding together two panels of the K-braced tubular-steel framework. The outer surfaces of the building beams and columns were chipped back, exposing the reinforcing rods. Anchor bolts welded to the inside face of the frame extended in toward the building. Grout poured in after the frame was assembled anchored it both to the building and to the foundation. (b) Building 113 as it now appears with the stiffening frame in place.

Some Personal Recollections of the January 1980 Earthquake

Jim Frank, Physicist: I was in the auditorium of the Nuclear Chemistry Building to hear a talk on the oil shale program. At 11 a.m., we noticed a slight rolling motion. "Ah, a minor earthquake," thought the old timers. But the rolling and shaking continued for half a minute, getting larger in amplitude. Then a really big jolt, like the final snap in "crack the whip," gave the sensation that the building was tilting to the southeast.

Two long (two- by six-foot) loudspeakers, hanging from the ceiling on either side of the platform, dropped loose at one end and swung to the floor. At the same moment, the lights flickered and the room darkened momentarily. I thought, "If it's like this in Livermore, what must be left of San Francisco?" People started leaving the auditorium rather calmly, except for one fellow behind me who knocked over a chair, or perhaps he had tried to get up during the waves and had trouble keeping his balance.

I grabbed one of the Lab bicycles parked in front of the building and rode to Building 111, where my office was. People were gathered in the streets, and I had to slow down to avoid pedestrians who weren't looking where they were going.

Building 111 had been evacuated, and no one was allowed to go back in. I exchanged "Where were you when?" stories with friends and bystanders. The most spectacular was told by Edward Teller's secretary. She was talking on the phone when the waves began, said "Excuse me a moment," and dived under her desk, telephone in hand, just as the final jolt threw several free-standing, six-foot-tall bookcases onto her chair. They had had to dig her out. I visited her office the next day—books and folders were everywhere, three feet deep.

John Verity, Library Division Leader: I was participating in our Department meeting in Building 121, about 50 yards down the hall from the library. It was around 11 o'clock and our meeting was just winding up when the earthquake hit. It felt like somebody had picked up the whole building about three feet and just dropped it, a very sharp jolt and then a series of jolts, and a number of us realized that an earthquake was going on. We dove under (then Deputy Department Head) Bob Spencer's conference table, and the knickknacks around his office were falling on the floor and breaking. A water pipe in the ceiling broke, and water was spraying down on the floor.

Under the table, I was thinking about our stacks in the main stack area. These had always been, to my mind, not terribly stable. You could push on them and they would rumble ominously, yet the sway bracing in them was supposedly adequate for their stability. They were braced at the top with a single iron bar that ran the whole length of the stacks.

Immediately after the earthquake was over, I ran down to the library, and my worst fears were confirmed. About 25 ranges of stacks in which we keep our heavy, bound journals, loaded to full capacity, had gone over like a series of dominos (see Fig. 1a on p. 2). The people present in the room at the time said the stacks had rattled alarmingly and swayed back and forth several times. They had picked up a periodic motion from being connected together at the top; each time they swayed a little more and finally they went over.

When I arrived, I was looking at a pile of books and twisted steel four or five feet high. My first thought was, "My God, is anybody under there?" Because you couldn't really tell if anybody was buried. I walked up and down the stacks, and I couldn't hear or see anything, there were no human parts sticking out of the mess, so I assumed that nobody was there. Then I got the library part of the building evacuated. (It was later confirmed that no one had been caught in the falling stacks.)

Dick Crawford, Monthly Reports Editor: The Monthly Reports Group was then housed in a trailer just outside the main library in Building 121. My first hint of the earthquake was when my Wang word processor started to slide off the table into my lap. I grabbed it and held on. Editor June Canada, seated opposite me, was trying to keep a bookcase from toppling on her. The trailer we were in swayed interminably, then dropped, and the power failed.

When the shaking stopped, we started picking up the classified materials we had been working on. Then, someone noticed that the trailer doors wouldn't open. We banged on the door, and technical illustrator Ulysses Falls came and pulled back the iron stairs, freeing the door. The trailer had fallen off its pedestals, back onto its wheels, dropping it slightly below the level of the stairs so that the doors were blocked (see Fig. 1b on p. 2).

determine accurate epicentral locations for many of the reported earthquakes. We are well prepared to study future earthquakes that strike the area, however. In conjunction with the U.S. Geological Survey, we have established two local seismographic networks, one of highly sensitive seismometers to record the components of the smallest earthquakes within the Livermore Valley and the other to record the strongest earthquakes.⁴

The sensitive seismometers enable us to pinpoint earthquake source locations accurately, a vital piece of information needed for a complete earthquake hazard analysis. Monitoring microearthquakes will help us to delineate zones of earthquake activity and to determine ambient seismicity levels throughout the Livermore Valley. These seismometers are so sensitive that we were able to calibrate them by measuring ground-wave travel times from relatively small explosive detonations.

The network of strong-motion seismometers, designed to record accelerations of up to 10 m/s^2 ($1g$) in three orthogonal directions, provides quantitative data on ground shaking, both for analyses of the free-field ground motion caused by a large earthquake and for the follow-up assessment of possible structural damage and personnel safety. (Because there were no strong-motion seismometers installed at LLNL during the 1980 earthquakes, we can only estimate peak accelerations at the site from measurements recorded at the nearby Veterans Hospital and at the Del Valle Dam, 1.7 and 2.6 m/s^2 , respectively.) This strong-motion network also will help us assess whether the geology under and near the Laboratory can locally amplify ground shaking.

We chose digital seismometers for most of the strong-motion network because of their wide dynamic range (66 dB), pre-event memory, and relatively easy data recovery. Their digital tape

cassettes can simply be inserted into a playback device to obtain a strip-chart accelerogram. These cassettes can also be read directly into a computer for spectral analysis and other detailed studies.

Analog instruments represent earlier technology; they have a more limited dynamic range (48 dB) and a more difficult data recovery procedure. Because they are so reliable, however (given adequate maintenance), we have included some in the strong-motion network. If some of the digital seismometers fail to operate correctly during an earthquake despite all precautions, we can be confident that the analog instruments will still record the event.

Summary

Our first-hand experience of seismic destructiveness in the 1980 earthquakes suggested many measures for improving the Laboratory's seismic safety. Many of these already have been implemented, and we are continuing to evaluate potential seismic hazards at the site and to consider further improvements where appropriate. □

Key Words: concrete—crack repair; damage control; earthquake; emergency services; seismic safety.

Notes and References

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Geology of the Livermore Valley

We have ascertained that the principal seismic hazard at the Laboratory is from rare large earthquakes along faults of the San Andreas system.

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Since April 1979, we have been studying the geology, hydrology, and seismology of the LLNL site and surrounding area. Our objective is to obtain the necessary data to supplement our environmental impact report and to refine our estimates of earthquake and other local geologic hazards. These comprehensive studies have included a thorough review and evaluation of existing geologic, geophysical, and seismic literature, aerial photographic surveys, geophysical surveys, geologic mapping and exploration, subsurface studies, seismic studies, and soil dating. From these, we have compiled a detailed picture of our surroundings.¹

Physiographic Setting

LLNL is located in the southeastern portion of the Livermore Valley, an east-west trending structural and topographic depression about 25 km long and about 11 km wide. The valley is within the Diablo Range of central California but is at approximate right angles to the generally north-northwest structural grain of the region. Over the ages, the sides of the Livermore Valley have been gradually moving apart (a motion that appears to be continuing). The resulting cleft has been filled with sediments, which are as deep as 1.2 km in places.

The valley floor is flat except for occasional hills. It rises gradually from an elevation of 92 m at its southwest corner to about 220 m at its eastern margin. Geologic studies indicate that some of

the hills, which rise as much as 46 m above the valley floor, were formed by uplifts of older rocks along fault lines. One group of such hills is about 1 km south of the Laboratory site, another is 3.4 km to the northwest.

The LLNL site has a rather smooth land surface (it was once an airfield) that slopes gently toward the northwest. Except for the banks of the Arroyo Seco and the side slopes of various open drainage ditches, the surface gradients are generally less than 3%. The total relief is 32 m over a distance of 1.9 km from the southeast to the northwest corner.

Geologic Setting

The Diablo Range is part of the California Coast Range province and consists predominantly of a core of metamorphic and igneous rocks of the Mesozoic Franciscan assemblage (the sort of rocks that form in a submarine trench adjacent to a continent). Beside and sometimes faulted over these rocks are layers of shallow marine sediments of similar age, known as the Great Valley sequence. The rocks that, nowadays, often separate these two totally different formations represent oceanic crust and upper mantle that originally was below the Great Valley rocks. An extinct subduction zone, known as the Coast Range thrust fault system, is presumed to be responsible for bringing together rocks of the Franciscan assemblage and the Great Valley sequence.

The San Andreas fault zone, one of the best-known features of the Coast Range province, extends more than 1200 km from the Gulf of California in the south to Shelter Cove, California, in the north, and passes 58 km southwest of the LLNL site (Fig. 1). In the past 50 million years, the western side of this fault zone has moved northward with respect to the eastern side by about 300 km.

In central California, there is geologic evidence for nine earthquakes large enough to cause surface ruptures along this fault system during the period extending back from the 19th to the 6th century A.D. The recurrence interval for earthquakes in this series ranged from 50 to 300 years, with an average of about 160 years. The last major earthquake on this fault was the source of the great San Francisco earthquake of 1906, which had an estimated Richter magnitude of 8.3.

Seismic activity continues today along this major fault system and its branches, the Hayward and the Calaveras fault zones. The long-term annual slippage

rate on the San Andreas fault is about 12 mm. The annual slippage on both the Hayward and Calaveras faults is about 7 mm. These latter fault zones are closer to the LLNL site (26 and 17 km, respectively) but they also are much shorter than the San Andreas fault, which limits the maximum credible earthquake attributable to either of them.

In addition, a number of smaller faults lie within the Livermore Valley and thus come much closer to the LLNL site. These include the Greenville fault, the Las Positas fault, and such lesser breaks as the Tesla, Verona, Corral Hollow, and Patterson Pass faults. The epicenters of the earthquakes that damaged buildings at LLNL in January 1980 were on the Greenville fault.

In all, more than 20 minor faults have been reported for the Livermore Valley, most of which appear to be inactive. (In addition, the evidence for the existence of some of these faults is unconvincing.) Some of these faults have been identified from aerial photographs and others by hydrological measurements. In a few

Fig. 1

Major fault zones in the San Francisco Bay Area, of which the San Andreas (extending more than half the length of the state of California) is the most famous. The Greenville fault was the source of the damaging earthquakes that rocked the Livermore Valley in January 1980. The Calaveras fault was the source of the April 24, 1964, earthquake that was centered 40 km from the Laboratory near Morgan Hill.

Fig. 2

(a) Photograph of the face of a road cut about 1 km south of the LLNL site, where a south branch of the Las Positas fault zone is exposed. Few fault zones are as clearly delineated as this; often, the rock types on both sides of the break are so similar that it takes a trained eye to notice the discontinuity. (b) The distribution of rock types on this cut.

(a)

(b)

cases, as for the Las Positas fault, there is direct visual evidence in cuts made for roads (Fig. 2).

Aerial photography is extremely useful for mapping of faults, providing a bird's-eye view of the terrain and of subtle changes in tone and texture that may reflect discontinuities in the deep underlying structure. Most revealing in this area are photographs taken in 1940 before the Laboratory site was developed (Fig. 3). Aerial photography demands careful interpretation, however. Many suspected lineaments, on closer inspection, turn out to be old stream beds or other purely surface features. Interpretation of such photographs

further the work of fault mapping by finding features that merit further study. In most cases, however, only direct observations on the ground can confirm which of these features are actually active or inactive faults.

The State of California defines an active fault as one that has moved perceptibly in the past 11 000 years.² The Nuclear Regulatory Commission has adopted the more stringent criterion of a single displacement in the past 35 000

years or multiple displacements in 500 000 years.³ For the purpose of these studies, we have adopted an intermediate standard of a single movement in the past 35 000 years.

Age Dating

We need some way to date tectonic movements, in part because the definition of fault activity depends on the length of time since the most recent

Fig. 3

Aerial photograph of the eastern Livermore Valley taken in 1940 while the area was still completely agricultural. Some of the apparent lineaments and tonal changes are associated with active or inactive faults, especially at the margins of hilly upthrust regions. Others represent old stream beds or other surface features unconnected with seismicity.

observable displacement. Since a buried fault cannot move significantly without disturbing the material lying on top of it, one way to date fault movements is to establish the ages of the undisturbed overlying sediments.

The floor of the Livermore Valley consists predominantly of continental alluvial deposits (sediments deposited in lakes and flood plains rather than in the ocean), more than 1 km deep in places, of latest Tertiary and Quaternary age

(Fig. 4). A complex pattern of regional deformation, uplift, erosion, and deposition can be read from these sediments, including the effects of variations in climate during late Pleistocene and Holocene times to the present. These variations enable us to assign relative ages to the various distinguishable deposits, which can later be calibrated when absolute age data become available for a few layers in the whole sequence.

Fig. 4

A generalized stratigraphic column for the Livermore Valley illustrating the widely varied kinds of deposits, most of them sedimentary. Of the rest, tuff is compacted volcanic ash, gabbro is mafic rock that solidified slowly deep underground, and pillow basalt is lava that was extruded deep underwater on the ocean floor. The first column identifies the geologic ages represented, with a few approximate dates. The descriptions in the last column include the kinds of fossils found in the strata.

Generalized Columnar Section—Tesla Quadrangle					
Age, millions of years	Formation		Thickness, m	Description	
Quaternary	Alluvium Terrace deposits		?	Gravels, sands, silts, clays	
1-5 Plio-Pleistocene	Tulare and Livermore gravels		1200	Continental deposits of gravels, sands, clays; tuff dated at 4 million years	
8-20 Upper Miocene	San Pablo Group	Neroly	Upper	600+	Shales, blue sandstone, tuffs
			Lower	15-210	Blue sandstone, andesitic conglomerates, tuff; fossil bones and leaves
		Clerbo		30-150	Granuliferous white sands, buff sands, tuffs, conglomerate, coal; fossil shells
Middle Miocene	Oursan?		210	Tan sandstone, tuffaceous shales; fossil bones and shells	
40 Middle Eocene	Tesla		600	Buff sands, white sands, clays (marine); fossil shells Buff sands, chocolate shales, coal (brackish-water); fossil leaves and shells	
70-90 Upper Cretaceous	Moreno Grande		10-200	Buff sandstone at top locally, siliceous, argillaceous, and sandy shales, limestone concretions, sandstone beds; fossil shells and foraminifera	
	Panoche		3000+	Concretionary and massive sandstone, argillaceous and silty shales, conglomerate; fossil shells	
Lower Cretaceous	Horsetown		0-150	Dark shales, sandstone; fossil shells	
Coast Range Thrust Fault					
70-150	Franciscan and related intrusive rocks		4500?	Sandstone, shales, chert lenses, conglomerate	
Pillow basalt					
Glaucophane schist					
Serpentine, diabase, diorite-gabbro					
Jurassic and Cretaceous					

As part of our site analysis, we drilled and logged 23 exploratory boreholes. In addition to the conventional geologic examination of cores and cuttings, we used other geophysical logging methods such as measurements of resistivity and natural gamma radiation. We applied these same logging techniques to an additional 16 wells drilled as part of our hydrologic investigation (Fig. 5).

We have obtained one absolute age by the carbon-14 dating method and several dates of soil-forming carbonate rocks by the thorium-uranium clock. In most cases, these dates correlate well with the relative ages deduced for the sediments from which the samples were obtained. On the basis of these data, we deduce that the alluvium beneath the Laboratory at depths of 1 to 5 m was deposited 35 000 to 100 000 years ago. An erosion surface, formed at least 300 000 years ago, lies 12 to 21 m below the present surface. The ages of these features serve to date the period of inactivity of any fault that has not disturbed them.

Geodetic Measurements

Benchmark surveys and triangulation and trilateration measurements make it possible to document the slow tilting and buckling of the earth. In some cases, these tectonic strains are dissipated harmlessly as they accumulate by creep and small earthquakes distributed over a wide zone. In other cases, strains can build up until they are released in a destructive earthquake.

Geodetic measurements in and around the Livermore Valley indicate that:

- Vertical ground movements change from subsidence to uplift in the vicinity of the Calaveras fault and that the floor of the Livermore Valley is sinking while the adjacent hills are rising.

- Tectonic creep measured along the Pleasanton fault from 1964 to 1969 was apparently terminated by the Danville swarm of earthquakes in 1970. No further creep was observed in the resurveys of 1974 and 1979.

- At the east margin of the Livermore Valley, near the LLNL site, there is another line of change from ground subsidence to uplift. At one time, a fault

was postulated here, but we have found no corroborative evidence of faulting on this line despite intensive investigation. It has been suggested that the subsidence may be caused by groundwater withdrawal, which would be difficult to separate from areal tectonic subsidence, but there are no known major groundwater withdrawals in the vicinity.

- A correlation appears to exist between minor subsidence southwest of Patterson Reservoir and withdrawal of oil from the Livermore oil field (to the east of the LLNL site).

Seismology

LLNL is in a seismically active region, and any major earthquake on the San Andreas, Hayward, or Calaveras fault zones to the west would produce strong ground shaking here. It has been estimated that a magnitude 8.3 earthquake, similar to the San Francisco earthquake of 1906, centered where the San Andreas fault approaches within 58 km of the Laboratory, would cause

Fig. 5

LLNL site map showing the locations of exploratory excavations undertaken in connection with this study. Circular dots represent boreholes and hydrologic wells that we drilled and logged with calipers and geophysical measurements of electrical resistivity, self-potential, and natural gamma radiation. Cores recovered from these drillings provided specimens of the various subsurface layers, including samples suitable for age dating by carbon-14 and by thorium decay. Colored bars represent trenches (up to 6 m deep) dug to expose possible evidence of surface faulting.

● Wells and boreholes
— Trenches

a peak acceleration at the LLNL site of 4 m/s^2 (0.4 g). Estimated peak accelerations at LLNL for the maximum credible earthquakes on the Hayward and Calaveras branches of the San Andreas fault zone are 3.5 and 5 m/s^2 , respectively. By contrast, the peak ground acceleration at our site from the recent strong earthquake (April 24, 1984, magnitude 6.2) on the Calaveras fault, centered 40 km away near Morgan Hill, was only 0.2 m/s^2 .

In January 1980, the Greenville fault, which runs along the eastern edge of the Livermore Valley and comes within about 400 m of the LLNL site, removed all doubts as to its seismic potential. In the space of three days, the Livermore Valley was shaken by four earthquakes with magnitudes ranging from 4.2 to 5.8; peak ground accelerations at LLNL were in the range of 2 to 3 m/s^2 (see the accompanying article on p. 1).

We also are monitoring microearthquakes that appear to correlate with the Las Positas fault along the southeastern border of the Livermore Valley. There is geologic evidence of fairly recent movement along this fault.

Among the 20 or more other faults that have been identified or postulated in the Livermore Valley region, the Concord-Green Valley, the Verona, and the Williams faults are known or postulated to be active. Some of the rest are unconfirmed and may not exist, at least as near-surface features, and the others appear to be either inactive or of uncertain status. In any case, none of these local faults has the right combination of length and proximity to contribute significantly to the cumulative seismic hazard at LLNL.

Recent geologic studies suggest that there is an old, inactive fault deep beneath the Laboratory site that we have named the "ancestral" Greenville fault to distinguish it from the roughly parallel modern Greenville fault. The ancestral fault has no geomorphic expression and no discernable effect on groundwater levels and late Quaternary alluvial deposits in the 5 m below the present surface. The ancestral fault also appears to have been displaced by branches of the active Las Positas fault. The

geologic evidence supports the belief that this fault has been inactive for more than 300 000 years.

Seismic Hazards

Previous assessments of the seismic hazard at LLNL were deterministic; that is, they considered only the largest historic earthquake on each of the surrounding faults and estimated the maximum ground motion at the LLNL site if the same earthquake should originate on the same fault at its closest approach. Although this approach to seismic-hazard analysis is widely accepted, it does not include a consideration of probability. What is the likelihood of a larger-than-historical earthquake, for example, and what is the chance that any earthquake will actually originate at the point of closest approach to our site?

To answer such questions, we have been using a probabilistic approach that allows us to take into account ranges of magnitudes and probability distributions. The probabilistic approach involves the concept of risk, which is defined as the product of the magnitude of an effect and its likelihood of happening. Thus, a very large but improbable event can involve less risk than a minor but very frequent event. (Similar reasoning is used by actuaries in computing the appropriate insurance premium for covering the range of possible claims associated with a specific hazard such as an automobile accident.)

The major benefit of the probabilistic approach is that the estimates it provides are more realistic than those of deterministic methods. The final result of a deterministic analysis is a single number representing the magnitude of the maximum credible earthquake. Realistically, however, a larger earthquake is always possible. If one were to occur, it would invalidate the entire deterministic analysis. Because a probabilistic analysis explicitly takes into account the possibility of larger-than-historic events, any earthquake that happens (no matter how large) simply extends the data base.

Because no strand of any modern fault crosses our site, the possibility of

surface rupture within the Laboratory during a major earthquake on either the Greenville or the Las Positas fault is nil. We regard the possibility of ground rupture along the inactive ancestral Greenville fault as extremely remote. Judging by the age of the overlying undisturbed sediments, there has been no displacement along this fault for 300 000 years at least.

In addition, we consider secondary seismic effects such as soil liquefaction and landslides to be very improbable. Soil liquefaction ordinarily takes place in regions where saturated subsoil lies close beneath the surface. Our subsoil, however, is mostly relatively dry sand and gravel (the depth to water-saturated sediments beneath our site ranges from about 14 to 49 m). Similarly, the LLNL site contains none of the steep hillsides normally associated with landslides.

Water Damage

Because the floor of the Livermore Valley is so flat, the question of drainage and possible flooding naturally arises. When the valley was first settled, there was an intermittent lake in the Pleasanton area. Around the turn of the century, this lake was drained to permit agriculture, and the drainage was later improved to allow urban development. There is still an area of enclosed drainage in the northeastern corner of the Livermore Valley, producing a shallow intermittent body of water known as Frick Lake.

Water from the entire Livermore Valley flows out through the south-flowing Arroyo de Laguna into the Alameda Creek drainage system and eventually into San Francisco Bay. If the Arroyo de Laguna were closed off during a heavy rainstorm (by a massive landslide, for example), severe flooding could take place at the west end of the Livermore Valley. Long before such flooding could reach LLNL, however, water would spill over into the San Ramon Valley and flow northward to the San Francisco Bay.

On the Laboratory site itself, a few dry creeks and drainage ditches provide for run-off of even heavy rains. Some erosion and sloughing could occur along

the banks of these channels during a major storm. We could also experience localized sheet flooding and erosion near the Arroyo Seco channel at the southwest corner of our site during a catastrophic storm.

Another possible source of flooding at our site is the South Bay Aqueduct, which comes within 400 m of the southeast corner of our site. A complete break at this close approach could produce sheet flooding over most of the LLNL site to a depth of about 1.5 cm.

Summary

Using a variety of advanced geophysical and geologic techniques, we have investigated the physiographic and seismologic setting of the LLNL site. The Livermore Valley is located in a seismically active region, and several active faults come within a few kilometres of the Laboratory. However, we have established that no active fault traces cross our site.

The work of establishing a maximum credible earthquake for our site continues. Previous deterministic estimates indicate that a peak ground acceleration of 5 m/s² could be experienced here as a result of an earthquake on the Calaveras fault 17 km to the west. We are using probabilistic analysis methods to estimate the likelihood of such an earthquake and the degree of risk associated with it. □

Key Words: age dating; earthquake; fault, active—Calaveras, Greenville, Hayward, Las Positas, San Andreas; fault, inactive—ancestral Greenville; geologic hazard; probabilistic analysis; seismic hazard.

Notes and References

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Monitoring Groundwater Quality at Site 300

We have designed and installed a state-of-the-art groundwater monitoring system at Site 300 to guard against the possibility of environmental hazards from our solid-waste disposal pits; preliminary groundwater analyses reveal that our disposal pits do produce low levels of contamination, and long-term monitoring is continuing.

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Weapons research often entails testing of explosive components. Such tests require realistic models of devices containing explosives that, to function properly, must contain some nonfissile materials identical or closely similar to those used in the actual nuclear weapons. Some of these tests produce solid waste contaminated with traces of beryllium and depleted uranium.

Since 1953, we have been conducting these tests at Site 300, a 27-km² site in Alameda and San Joaquin counties in the eastern portion of the Altamont Hills about 20 km from our Livermore Valley site (Fig. 1). Most of Site 300 is covered with steep hills and rugged canyons, although in the southern portion there are some rolling hills with flat benches and valleys.

We have been burying the by-products from these tests in landfill disposal pits. In 1981, we started a program to evaluate whether these landfills have had any significant effect on groundwater quality. The overall objective of this program was to evaluate the eight existing solid-waste landfills, to determine whether any groundwater contamination has occurred as a result of disposal operations, and to document the

present condition of the groundwater as a starting point for future studies.

Program activities included characterization of the geology and hydrogeology of the site and the migratory tendencies of any hazardous waste substances currently buried there. As part of this investigation, we designed and installed a state-of-the-art groundwater sampling network and implemented a detailed sampling and chemical analysis program to evaluate groundwater quality in the vicinity of the landfill areas. Many of the wells drilled for this investigation will be used for continued environmental monitoring.

Figure 2 shows the locations of the eight landfill pits at Site 300. The two presently active landfills are pits 1 and 7. The buried contaminated debris consists of three classes of material:

- Equipment and handling materials (paper, cloth, setup apparatus).
- Firing-table debris (dirt, gravel, concrete).
- Metallic parts.

On an annual basis, this amounts to about 850 kg of depleted uranium and 125 kg of beryllium in debris that occupies about 1600 m³ and weighs 71 000 tonnes.¹

Our investigation involved a multidisciplinary Laboratory effort and was undertaken in three phases. First, we performed a preliminary survey of regional and local geologic, hydrologic, geochemical, and geophysical conditions to select the drilling locations that would most effectively minimize the costs of exploratory drilling. We then designed the groundwater sampling network, drilled the necessary wells, installed the equipment, and performed initial chemical sampling and analysis. Finally, we interpreted the preliminary results, made final changes in the groundwater sampling network, and performed additional sampling and chemical analyses.

General Approach

The overall objectives in the design of the groundwater sampling program were to verify the direction of groundwater flow across individual landfill areas and to establish the levels of any contaminants present in the groundwater. We applied state-of-the-art technology to accomplish these

Fig. 1 ▲

Site 300, located in a hilly area remote from population centers in Alameda and San Joaquin counties, is about 20 km from LLNL.

◀ Fig. 2

Locations of solid-waste landfill pits 1 through 8, groundwater monitoring wells, exploratory boreholes, and other boreholes used in our investigation. Also shown are water supply wells, undeveloped wells, and springs. Arrows indicate the prevailing direction of groundwater flow on either side of the Patterson anticline, which passes through the site between Buildings 850 and 851. Trenches T-1 and T-2, shown here, were dug to investigate faults that proved to be inactive.

objectives with as few wells as possible despite a complex, variable, and deep hydrologic system.

Any study of a region's hydrology is incomplete without thorough knowledge of its geology. At the outset of this study, we needed detailed geologic information at each pit site on which to base prudent choices for borehole locations. Because existing geologic maps were inadequate, we carried out field studies to establish a detailed local stratigraphy and prepared detailed geologic maps (1:2400 scale) of the immediate area around each disposal site. We also prepared preliminary geologic cross sections to outline the expected subsurface conditions at each drilling site.

We obtained information useful in selecting optimum sites for the monitoring wells by applying surface geophysical techniques such as dipole-dipole resistivity and terrain conductivity. These techniques give estimates of the depth and geometry of the surface of the saturated zone (depth to the water-table aquifer, the uppermost water-bearing formation) and can provide gross evidence of possible contamination beneath the landfills if the contaminant produces a sufficient conductivity contrast. Dipole-dipole resistivity is best suited to determining changes in electrical properties with depth. Terrain conductivity provides an easy way of

tracking lateral changes in electrical properties at a particular depth (see Fig. 3). The use of such methods is relatively new in site assessments, especially under the variable hydrogeologic conditions present at Site 300.

Both dry rock and pure water are insulators, but a bed of wet rock can be highly conductive. This apparent paradox comes about because the interstitial water in rock is seldom pure, having dissolved material. Water with enough dissolved material in it can have a relatively high conductivity. Deposits with contrasting electrical properties (such as sandstone and claystone), especially if their boundaries are irregularly shaped, can interfere with the interpretation of geophysical data and can make it necessary to obtain additional information about geology and groundwater conditions.

Once we established the locations of the monitoring wells for all landfill areas, based on the integration of all available data, installation could begin. The key to constructing a high-quality sampling system that will yield representative groundwater analyses is to minimize sampling-induced changes in the subsurface chemistry near the wells and to understand and allow for any changes that do occur. Therefore, individual sampling wells were designed using methods, equipment, and materials

Fig. 3

Terrain conductivity data (converted to resistivity in ohm-m) in the vicinity of pit 6, for a depth of investigation of 15 m, helped us decide where to locate our monitoring wells. Locations of the measurement sites (spaced 20 m apart), monitoring wells, and an exploratory borehole are shown; the colored lines are elevation contours (in metres).

intended to minimize changes in the chemical characteristics of the groundwater. For example, it was imperative to avoid drilling into the landfills, since it would then be impossible to know whether any contamination found in the groundwater was due to contaminant migration or was merely a result of drilling activities.

Furthermore, we had to take special precautions to prevent cross-contamination among wells and among individual sampling points. Because our objective was to measure traces of impurities, even a small amount of material adhering to drilling equipment could create a false appearance of contamination. To avert this possibility, we rigorously decontaminated the drill rig and all equipment by initial steam cleaning and thereafter by hole-to-hole washdowns.

Air-rotary drilling was our method of choice, although drilling with local water as the circulating fluid was also acceptable. This was done because we wanted to avoid potential contamination readings due to additives used in proprietary drilling muds and foams. These additives have been found to remain in the borehole despite vigorous flushing.²

To maximize sampling integrity, hydrogeologic information, and cost effectiveness, we chose a drill rig capable of both soil sampling and continuous coring. This involved augering in unconsolidated and decomposed material (taking soil samples at 1.5-m intervals) and air-rotary or wireline core drilling in rock. We monitored the samples in the fie. for both volatile organics and radioactivity.

We ran caliper, electric, and natural gamma logs in the open boreholes of all monitoring wells and logged the drill cuttings and cores in accordance with accepted professional practice. The information obtained from core-logging activities and from soil and rock core samples is essential to an understanding of the hydrogeology and groundwater geochemistry at individual landfill sites. A knowledge of geochemical rock-water interactions can help to explain unusually high natural concentrations of

inorganic chemicals, which may sometimes exceed allowable limits for drinking water.

Because groundwater moves both up and down as well as horizontally, piezometric heads (that is, water pressure) in an aquifer may differ significantly, both from top to bottom and between successive aquifers. Therefore, these relationships must be established to determine potential vertical flow paths. Also, concentrations of different contaminants within an aquifer may vary widely from place to place, both vertically and horizontally. To detect these variations, it is usually desirable to install a series of wells open at different depths in the geologic units.

Depending on the hydrogeologic conditions, a wide variety of monitoring-well designs may be satisfactory. For Site 300, we decided that the most effective system would use a combination of sampling wells. Some of these would have a single sampling point, others would have multilevel piezometers (several isolated sampling points within a single borehole). We designed these sampling wells for long-term monitoring of specific zones.

Previous studies have indicated that contaminants may travel in discrete lenses within a given aquifer. Where the water-table aquifer was thick enough, we therefore provided for preferential sampling of different levels within the one aquifer. It was also necessary to understand the potential vertical migration of any groundwater constituents to evaluate whether constituents found in the water-table aquifer could migrate to deeper aquifers. To do this, we had to measure hydraulic head potential in the isolated water-bearing zones.

At present, there are only two commercially available multilevel sampling systems. We considered designing and fabricating our own system but decided against it because of the expense and delays involved. Instead, we chose a commercial positive-displacement sampler, made of chemically inert materials, that uses high-purity nitrogen to drive the water sample to the surface for collection,

thereby minimizing the effects of vacuum suction and aeration associated with other samplers (which would alter the composition of the sample).

However, these particular samplers lack a means to monitor hydraulic head

Fig. 4

An instrumentation package consisting of a gas-driven groundwater sampler and a pressure transducer. An alumina filter surrounds the sampler, which is connected to the surface by a dual-bore sample tube (one bore supplies the gas to drive the water sample up through the other). The pressure transducer and the sampler are packed in sand held in place by a polypropylene sock.

Fig. 5

A typical sampling well used in our groundwater study, showing two isolated deep sampling locations, a standpipe piezometer for shallow water measurements, and an access tube for neutron backscatter measurements of moisture in unsaturated nearsurface soil. (Horizontal dimensions are greatly exaggerated.)

potential (aquifer pressure) in deeper wells. Therefore, at a number of locations we attached an electric piezometer (a remote pressure transducer) to the sample tube just above the sampler. We placed these instrumentation packages, enclosed in a polypropylene filter sock backfilled with No. 3 sand (Fig. 4), at selected depths (depending on the hydrogeology) and permanently isolated them from each other with plugs of bentonite or grout. In each well, we also installed a standpipe piezometer to monitor the water-table aquifer.

Figure 5 illustrates a typical completed well. At some locations, where the water table was shallow, we placed only a single standpipe piezometer and used the well only for monitoring the uppermost aquifer. We also installed a neutron access tube at each disposal pit to enable us to monitor moisture changes in the unsaturated zone.

All standpipe piezometers were constructed of inert high-purity polyvinylchloride, suitable for storing drinking water. All joints were flush-joint threaded (i.e., screwed together rather than glued) to avoid known problems associated with degradation and leaching of contaminants from organic coupling cements.³

New Drilling Techniques

In most kinds of water-well drilling, mixing of the groundwater from different levels is of minor concern. In our sampling wells, however, the objective was not only to obtain water but to determine accurately the composition of the water at different depths. It was therefore essential to obtain accurate samples at various levels, uncontaminated by water from any other level. To do this, we developed a new drilling technique that eliminates potential cross-contamination of groundwater between aquifers and allows for valid multilevel groundwater sampling.⁴ This method is very useful in instrumenting underlying confined aquifers when the water table is relatively deep, and the Department of Energy has applied for a patent on it.

Figure 6 shows the steps in the basic technique, which involves sealing a stainless steel casing section into the formation below the water-table aquifer and drilling the rest of the sampling well at reduced diameter through that casing. To do this, we drilled down to the top of the confining bed beneath the water-table aquifer, reamed out the hole to a diameter of 17 cm, and set in a temporary casing that ended 15 cm above the bottom of the borehole (Fig. 6a). The 2.4-m-long lowermost casing section was of stainless steel with a left-hand thread, joined to the right-hand-threaded carbon-steel casing above by a coupling with both right- and left-hand threads (Fig. 6b).

After the casing was in place, we poured grout both inside and outside the stainless steel casing section to a depth of 1.8 m and allowed it to set for 2 to 4 hours, immobilizing it. We then removed all standing water in the casing and allowed the well to stand for one to two hours to check for leaks in the casing or the grout seal through which formation water could enter (Fig. 6c).

Once we were sure there were no leaks, we drilled through the grout plug (at reduced diameter) and out the bottom of the casing through the confining layer into the lower aquifer to total depth (Fig. 6d). We then removed the drilling tools, ran geophysical logs in the bottom section of the hole, emplaced the lower sampler/transducer assemblies, and filled the borehole back up to the top of the stainless steel casing section with grout, sealing off the underlying aquifer. After the grout cured, we removed any standing water in the casing and again monitored the borehole for leakage into the temporary casing from below. When it had been determined that there were no leaks, we removed the temporary casing from the borehole by unscrewing it from the left-hand-threaded stainless steel casing (Fig. 6e).

This left the upper part of the borehole open to the formation, making it possible to emplace additional instruments. The completion of the well in the upper aquifer was similar to that in the lower aquifer except that a standpipe piezometer was installed as

the uppermost (water-table aquifer) sampling point. A schematic of a completed monitoring well is shown in Fig. 6f.

Hydrogeologic Implications

There are two major bedrock sequences at Site 300, both of which date from the Upper Miocene and are about 8 million years old. The Neroly formation is a bluish sandstone with claystone and conglomerate interbeds, and the Cierbo formation is a friable brownish sandstone unit beneath the Neroly. The overall geologic structure is dominated by the Patterson anticline, whose axis is located midsite (see Fig. 2), trending roughly east-west. An important factor in Site 300 hydrogeology, discovered during our investigations, is that the directions of regional groundwater gradients follow the dip of the bedrock sequence instead of the topographic gradients as one might normally expect.

North of the Patterson anticline, the bedrock dips gently (about 5 deg) to the northeast, and the groundwater flows in that direction (see Fig. 2). Therefore, if any contaminants from pits 1, 2, 8, and the pit-7 complex were to reach the water-table aquifer, they could migrate toward the northern boundary of Site 300. In the area south of the anticline (which includes pit 6), the groundwater flows south to southeast, toward Corral Hollow, also following the dip of the bedrock sequence.

We observed two main aquifers, a water-table aquifer and a deeper confined aquifer at the contact between the Neroly and Cierbo formations; the groundwater flow in both roughly follows the dip of the bedrock sequence. However, we also found a perched aquifer underneath the pit 7 area, isolated from the water-table aquifer by a thick sequence of claystone and partly limited in lateral extent by a fault that acts as a groundwater barrier. Flow in this perched aquifer is toward the southeast, following the local dip of the topography and an underlying impermeable bed.

Fig. 6

Steps in the emplacement of a deep sampling well to prevent mixing of groundwater from different levels.

(a) Straight borehole down into confining bed, showing composite casing with stainless steel end section. (b) Detail of right- and left-hand-threaded coupling joining carbon steel and stainless steel sections. (c) Grout inside and out to immobilize stainless steel section and seal bottom of pipe against groundwater leakage. (d) Borehole through grout plug and into underlying aquifer. (e) Installation of lower sampling devices and isolating plugs of bentonite or grout up to level of initial grout plug. Removal of casing except for stainless steel section. (f) Completion of sampling well.

Two major faults cross Site 300: the Elk Ravine fault in the north, with branches beneath pits 1 and 2, and the Carnegie fault along the southwest edge of the site, which passes beneath pit 6. We excavated exploratory trenches T-1 and T-2 (Fig. 2) across these faults and found no evidence of displacements in alluvial deposits that are at least 11 000 years old. Therefore, according to guidelines issued by the State of California and the Environmental Protection Agency, the faults are regarded as inactive and do not limit continued use of the active disposal pit 1.

Final Groundwater Sampling Network

We now have five discrete groundwater sampling networks at Site 300 to monitor hydrogeologic conditions in the areas of pits 1, 2, 6, 8, and the pit-7 complex (pits 3, 4, 5, and 7). The overall sampling network includes 21 new wells with a total of 30 sampling points (Fig. 2).^{5,6} Two additional exploratory boreholes also were drilled but were not completed as groundwater sampling wells. Because the water table was quite deep at several of the landfill locations, we drilled a total of about 1.2 km of borehole.

Our multilevel sampling wells contain two to four sampling points each and range in total depth from 48 to 120 m. All wells are permanently labeled, and surface instrumentation is housed in weatherproof enclosures. The sampler tubes are permanently connected to a prefabricated manifold mounted in the enclosure.

Figure 7, a cross-sectional view of part of the groundwater sampling network at disposal pits 1 and 2, indicates the detailed understanding of the local hydrogeology that our sampling network provides. The isolated sampling zones within individual boreholes are identified; the groundwater flows from southwest to northeast.

Chemical Sampling and Analyses

In the initial reconnaissance phase of chemical analyses, we sampled and analyzed waters from 12 springs and 10

already existing wells. In the second phase of sampling, we analyzed groundwater from the new monitoring wells in the vicinity of the landfills. These waters were analyzed for a wide range of inorganic and organic constituents (see Table 1). We used mass and alpha spectrometry to distinguish depleted uranium (typically containing only about one-quarter the normal amount of uranium-235) from naturally occurring uranium.

During the initial phase, we subjected the waters of the monitoring wells

to three sets of sampling, relying extensively on commercial, state-certified laboratories for measurements of selected chemical and radioactive substances. With each batch of samples, we also submitted both blanks and standards to ensure quality control.

We analyzed the soil samples obtained during drilling for beryllium, uranium, and volatile organic compounds. All sampling was done in a manner that preserved the geochemical integrity of the groundwater and soil samples, thereby ensuring the validity

Table 1 Chemical analyses performed on Site 300 groundwaters.

Field Analyses

pH, Eh (redox potential), dissolved oxygen, alkalinity, sulfide, electrical conductivity.

Laboratory Analyses for Inorganics

Cations (sodium, potassium, magnesium, calcium, strontium, silicon, iron, manganese, lithium, boron, aluminium, titanium, vanadium, phosphorous, cobalt, copper, nickel, zinc, uranium, beryllium).

Anions (chloride, nitrate, nitrite, fluoride, sulfate).

Toxic metals (arsenic, barium, cadmium, chromium, mercury, lead, silver, selenium).

Other (isotopic uranium, tritium, gross alpha, gross beta).

Laboratory Analyses for Organics

Total organic carbon, total Kjeldahl nitrogen, total organic halide, ammonia, high-explosive compounds (HMX, RDX, TNT, PETN), volatile organics, priority pollutants (selected samples), organochlorine pesticides, PCBs (selected samples), phenolics.

Fig. 7

Geologic cross section through disposal pits 1 and 2 on a southwest to northeast plane through sampling well K2-4, showing the various groundwater zones, the sampling locations within them, and the two branches of the Elk Ravine fault. The other four wells (K2-2, K2-1, K1-1, K1-2) are projected from their true locations to the southeast and northwest of the cross-sectional plane. This figure illustrates the detailed understanding of local geology provided by our geologic and hydrologic studies.

of the results. This included the use of proper sampling equipment and appropriate sample-preservation techniques and handling procedures.

Results

From these studies, we have established a chemical baseline for future groundwater monitoring. The uppermost aquifer at Site 300 was found to contain high levels of naturally occurring sulfate, sulfide, and uranium. This is due primarily to the nature of the Neroly formation and the presence of volcanic ash beds, which are relatively rich in uranium. Conditions in the underlying confined aquifer were generally reducing, which would tend to inhibit the migration of beryllium and most heavy metals, including uranium, that are much more soluble as oxides.

Surface water also played a part in determining landfill integrity. Pits 2 and 8 are located in ravines, enabling concentrated runoff to erode the top cover. We have now installed diversion ditches that carry the water around these pits, correcting this problem.

The earth covers on pits 1, 6, and the pit-7 complex (pits 3, 4, 5, and 7) appear to have low permeability and good erosion resistance. The cover at pit 1 consists of sandy clays or very clayey, gravelly sands. The cover at pit 6 consists of highly expansive sandy clays, the predominant surficial materials in the area. Similarly, soils in the vicinity of the pit-7 complex, which vary in composition from clayey, gravelly sands to silty clay, have been used for top cover.

Table 2 summarizes the important chemical results and general information

Table 2 Highlights of preliminary groundwater analyses and hydrology for the Site 300 disposal pits.

Pit	Average depth to water table, m	Number of monitoring wells	Number of sampling points (Depth range, m)	Groundwater flow direction	Initial chemical results ^a
1	38	2	5 (35-96)	N69°E	In deeper aquifer, arsenic (0.4 ppm) is higher in downgradient wells. However, rock analyses show natural origin. Nitrate increases (31 ppm) occur downgradient.
2	18	4	7 (17-64)	N69°E	Nitrate increases (30 ppm) occur downgradient. Tritium exceeds Site 300 baseline values in downgradient well K2-1 (1026 pCi/litre).
6	9	3	3 (21-29)	S15°E	Minor levels of organics (20-30 ppb toluene, methylene chloride) were detected in soils.
7 ^b	8 ^c	5	6 (12-40)	S59°E	Tritium increases (2150-3300 pCi/litre) occur downgradient in vicinity of landfills. Tritium increases (14,130 pCi/litre) occur further downgradient (Well K2-4). ^d Nitrate increases (25-32 ppm) occur downgradient.
8	45	3	5 (46-63)	N11°E	Depleted uranium (0.8 ppb) detected downgradient. Total uranium concentration is 7.2 ppb.

^aAll results refer to monitoring wells in the uppermost aquifer unless otherwise noted.

^bPit 7 complex includes Pits 3, 4, 5, and 7.

^cIndicates depth to perched water table. Actual water table (saturated zone) exceeds 96 m in depth.

^dWell K2-4 is downgradient from the Pit 7 complex. Although it is located in the vicinity of Pit 2, it appears hydrologically separated from Pit 2 by the Elk Ravine Fault, which acts as a groundwater barrier.

concerning the sampling network and depth to the water table at each disposal location. A trace of depleted uranium (0.8 ppb) was detected downgradient from pit 8. However, the total concentration of both natural and depleted uranium detected at pit 8 (7.2 ppb) is far below the concentrations of natural uranium in other Site 300 groundwaters, which range up to 740 ppb.

Part of the reason for the presence of depleted uranium in groundwater near pit 8 may be the erosion of the pit's top cover. Although the water table is fairly deep at this location, the bedrock consists of permeable materials and appears to contain numerous fractures. This could have increased the transport of any soluble buried constituents to the water table.

Downgradient from pit 1, arsenic was found to exceed drinking-water standards⁷ in the deeper aquifer. However, x-ray fluorescence analysis of the rock core from that particular sampling interval showed high levels of arsenopyrite naturally present in the rock, thereby accounting for the arsenic in the groundwater.

Nitrate was found to increase downgradient in the water-table aquifer from pits 1, 2, and 7. Tritium concentrations above background were detected downgradient in the vicinity of pits 2 and 7, and these levels are increasing. Minor levels of organics (primarily toluene) were detected in the soils at pit 6, but none in the groundwater. All other uranium detected, except at pit 8, was natural, and no beryllium was detected in any of the monitoring wells.^{3,8}

No other evidence of toxic substances due to solid-waste disposal operations at Site 300 was observed. In general, present results indicate chemical constituents typical of natural groundwaters, although depleted

uranium, tritium, and possibly nitrate are present due to materials in the disposal pits. Early detection of changes in groundwater quality is now possible, and actions are being taken to assess the effects of observed changes. The network of observation wells at Site 300 continues to be an important part of the Laboratory's environmental monitoring and compliance effort. □

Key Words: beryllium; contamination—groundwater; geophysical survey—methods; landfill; uranium—depleted, natural; waste disposal—solid.

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AAABSTRACTS

Earthquake Safety at LLNL

Motivated in part by earthquakes that shook LLNL in January 1980, we have undertaken an intensive program to strengthen Laboratory structures, utilities, and individual work stations and to reduce personnel risks and secondary damage potential from natural gas, fire, water, and other hazards.

Contact: Gary E. Freeland (415) 422-9411.

Geology of the Livermore Valley

Using advanced geophysical and geologic techniques, we have investigated the physiographic and seismologic setting of the LLNL site. The Livermore Valley, where the Laboratory is located, is known to be in a seismically active region, and several faults come within a few kilometres of LLNL. We have ascertained that the primary seismic hazard at the Laboratory is from rare, large earthquakes along faults of the major San Andreas system, particularly the Greenville and Las Positas faults and the more distant Calaveras fault zone.

Contact: Donald O. Emerson (415) 422-6504.

Monitoring Groundwater Quality at Site 300

The Laboratory's nonnuclear testing of explosive weapon components is conducted at Site 300; these tests produce solid wastes contaminated with traces of beryllium and depleted uranium that are buried in landfill disposal pits at Site 300. We designed a groundwater monitoring system to determine whether any groundwater contamination has occurred as a result of disposal operations and to document the present condition of the groundwater as a starting point for future studies. Current analyses indicate that low levels of contamination are present as a result of disposal-pit operations, and long-term monitoring is continuing to ensure that landfill disposal of these wastes does not adversely affect groundwater quality.

Contact: Ellen Raber (415) 422-3985.

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