

Lending a Hand to an

Livermore experts joined the international effort to end the

ON April 20, 2010, oil, gas, and cement exploded from the borehole of BP's Macondo oil well on the seafloor of the Gulf of Mexico, igniting the floating drilling rig Deepwater Horizon. The tragedy cost 11 crew members their lives, and the raging fire was quenched only when the rig eventually collapsed and sank. The well was, by then, leaking oil into the deep waters of the Gulf. Within days, Livermore scientists and engineers joined what became an international effort to plug the well and address the environmental damages caused by the massive spill, applying their expertise in engineering, modeling, and diagnostics to the largely unfamiliar arena of undersea oil-well technology.

The Laboratory's contributions to the response involved a short-term atmospheric modeling effort and a longer

Oily Problem

largest-ever undersea oil spill.

effort to provide technical capabilities and peer review to the U.S. Coast Guard–led endeavor to plug the leak. The Department of Homeland Security’s Interagency Modeling and Atmospheric Assessment Center (IMAAC) provided plume predictions of the April 23 fire on the Deepwater Horizon oil platform. The National Atmospheric Release Advisory Center at Livermore, which serves as the IMAAC operations hub, forecast the particulates that might be released from planned surface-oil test burns—one of several methods used to remove spilled oil from the Gulf. The center predicted the extent of particulate dispersal and the areas in which air-quality standards might be exceeded.

A week after the explosion, Secretary of Energy Steven Chu, at the direction of President Barack Obama, asked the

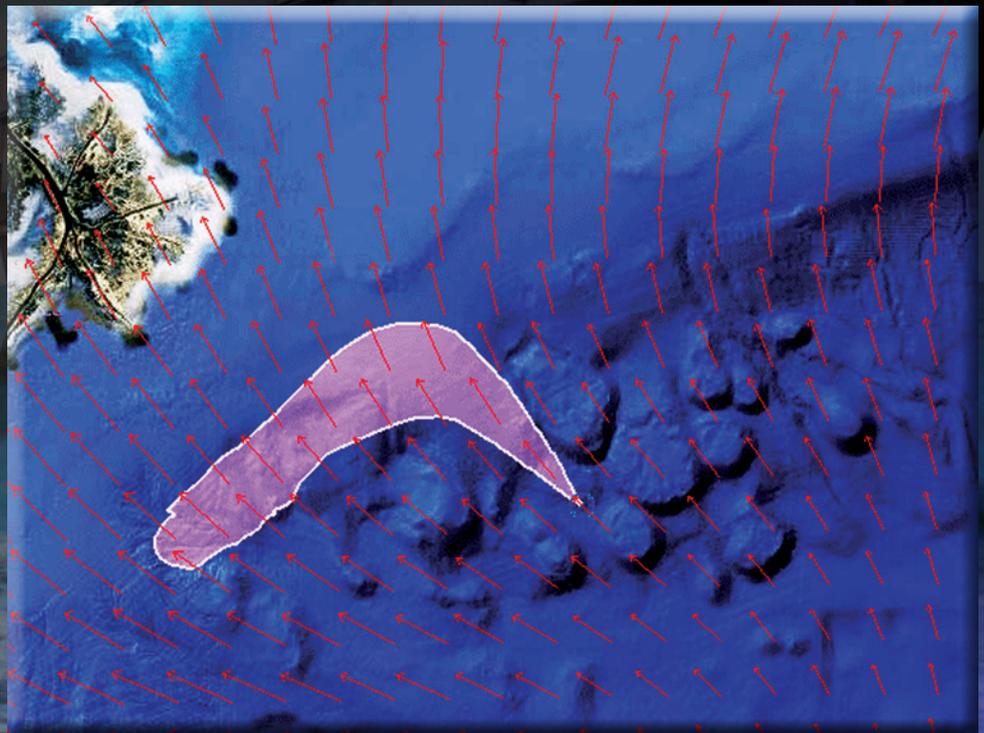
national laboratories to quickly come up with ideas for spill mitigation and environmental remediation. He also requested that Sandia, Los Alamos, and Lawrence Livermore national laboratories send personnel to BP’s crisis center in Houston, Texas, to assist with response efforts. (See the box on p. 13.)

Thus began a sustained advisory and technical support role for the three laboratories, both at the crisis center and back at their home sites. Working with BP, other oil companies, and government

agencies such as the U.S. Geological Survey and the National Oceanic and Atmospheric Administration, the three laboratories drew on their expertise and experience in areas such as diagnostics and fluid dynamics to support work to stop the oil leak.

The leak was securely capped on July 15, 2010, and on September 19, operations at the well site were successfully completed. Retired Coast Guard Admiral Thad Allen, who had overseen spill containment and mitigation,

Results from a computer model run by the National Atmospheric Release Advisory Center show the projected dispersal of smoke plumes from a surface-oil burn in the Gulf of Mexico. (Background map courtesy of Google.)



declared the well “effectively dead.” From late April until September, up to 60 Livermore engineers and scientists provided oil-spill analysis and assistance under the coordination of Rob Sharpe, the deputy associate director for Science and Technology in Livermore’s Engineering Directorate. Los Alamos and Sandia provided comparable technical expertise.

“Support from the three labs focused on flow, capture, and containment,” says Sharpe. “We soon demonstrated that the labs could offer expertise and technology

that were not in general commercially available to the drilling industry.” Bruce Warner, who led the Livermore task force assigned to assemble technical resources to aid the oil-spill effort, says, “Very quickly, it became clear that the national labs had the technology necessary to help. It was basically a self-selection process.”

Into the Deep

Two major challenges throughout the crisis were the undersea location of the well and the dearth of information

about the leak site and flow rate. Julio Friedmann, a geoscientist who serves as deputy program director for Energy and Environmental Security in Livermore’s Global Security Principal Directorate, says, “The Macondo well environment was inhomogeneous, and characterizing the geology near the surface of the seafloor was complicated.” Without understanding characteristics such as the effects of stress on rocks in the upper 200 meters of the oil well, scientists had to eliminate the more daring proposals, such as using



Fireboat crews battle the blazing remnants of the offshore oil rig Deepwater Horizon on April 21, 2010. An explosion in the Macondo well led to the catastrophic rig fire and oil leak. (Courtesy of U.S. Coast Guard.)

explosives to collapse the well casing. Detailed geologic information about the oil reservoir and seafloor topography was also often unavailable. Compounding the problem was that the blowout likely changed the conditions of the drilling structures and rocks around the well bore.

Even with thorough documentation and complete information, performing repairs on an oil well located under 1,500 meters of water posed enormous challenges. At this depth, water temperature is nearly freezing, and its pressure is about 17 megapascals—enough to compress a basketball to the size of an orange. BP used remotely operated vehicles (ROVs), which Sharpe describes as “relatively crude robots,” to acquire videos of the leaking well and perform most undersea operations.

Attached to ships by umbilical cables and controlled by operators onboard, the robots moved extremely slowly and, with their large claws, could perform only basic grasping and twisting maneuvers. Underwater activities were further limited by the robots’ 8-hour power supply and 140-kilogram lifting limit. “Operators might spend 15 minutes making the robot pick up a socket wrench, put it on a nut, and turn it,” says Livermore engineer Bob Ferencz. “They called it ‘undersea time.’ BP had to have a lot of contingency plans for each action in case something went wrong, for example, if a nut was distorted.”

Expertise in extracting information indirectly was crucial to understanding the state and stability of the well and its associated structures, how much oil was escaping the well, and where it was flowing. An early opportunity for the national laboratories was in helping BP diagnose the condition of the blowout preventer, a 20-meter-high mass of interconnected valves and piping that topped the oil well.

Blowout preventers are designed to close off a well should oil or gas

uncontrollably rush to the top—precisely the sort of event that precipitated the explosion and leak. Because the preventer on the Macondo well did not activate, the Deepwater Horizon crew had to abandon the rig. Extending from the top of what Sharpe called “a giant spigot for oil” was more than a kilometer of collapsed piping that originally linked the well to the Deepwater Horizon at the surface.

Now crumpled on the ocean floor, the piping was still connected at one end to the blowout preventer and had oil leaking from several spots.

Looking and Listening for Clues

Engineers needed to “see” inside the blowout preventer to determine why its five redundant valves did not sever the pipes and seal off the well. They also

At the Heart of Spill Operations

In addition to the “home team” scientific efforts at Lawrence Livermore, Los Alamos, and Sandia national laboratories, a small pool of scientists and engineers from the three laboratories worked shifts at the BP crisis command center in Houston, Texas. Twelve technical staff members traveled to Houston from Livermore, ensuring that at least one Laboratory representative was available daily, including weekends and holidays, from May to September. During a few key operations, the national laboratories’ team maintained round-the-clock coverage at the crisis center.

Livermore engineer Scott Perfect became known as the Laboratory’s Iron Man for volunteering the most time at the center. He saw his role and that of other personnel from the national laboratories as an intermediary. “We were in Houston conducting an orchestra at Livermore,” says Perfect. “We were reaching back to our home organizations, supplying them with information so they could do their work and communicate the results back to us in Houston.” Daily conference calls involving staff from the BP crisis center, national laboratories, and government agencies as well as Secretary of Energy Steven Chu ensured that all participants were well informed. Perfect notes that especially in the early stages, an essential part of his role was knowing the capabilities available at Livermore and the other national laboratories and recognizing opportunities where he could offer their resources. Livermore engineer Bob Ferencz, who also spent time in Houston, says, “It was an ongoing triage effort. We determined which issues had the highest priority and what lab could offer help on each one.”

This role evolved significantly as BP came to appreciate the depth of knowledge and experience available from the national laboratories and as Secretary Chu extended their involvement. Laboratory personnel in Houston spent much of the summer assessing designs and ideas presented by BP scientists. They asked questions, drafted procedures, looked for reactions, previewed concepts, and facilitated reviews to evaluate designs and suggest the best next steps. Representatives from the three laboratories also provided updates on containment efforts to the Department of Energy and at times the White House. Diane Chinn, a division leader in Livermore’s Engineering Directorate, notes that although the laboratories were rarely in a design role, they were vital in helping BP determine whether proposals for capping the well or collecting the oil would work.

Shifts at the crisis center were long, occasionally lasting more than 24 hours, and the stress level was high because of the disaster’s scope and urgency. But Livermore team members were glad they had participated. According to Perfect, the atmosphere of cooperation held its own appeal. “I enjoyed working with the people from the other labs,” he says. “We all shared the same sense of mission and duty.”

wanted to assess the structure's baseline state before proceeding with plans to cap the well. Sharpe notes that despite the unwieldy size and thickness of the preventer, x-ray imaging would have been

relatively easy aboveground. Underwater imaging was more challenging.

A Los Alamos team led by Scott Watson used gamma radiography to examine the blowout preventer. The operation involved

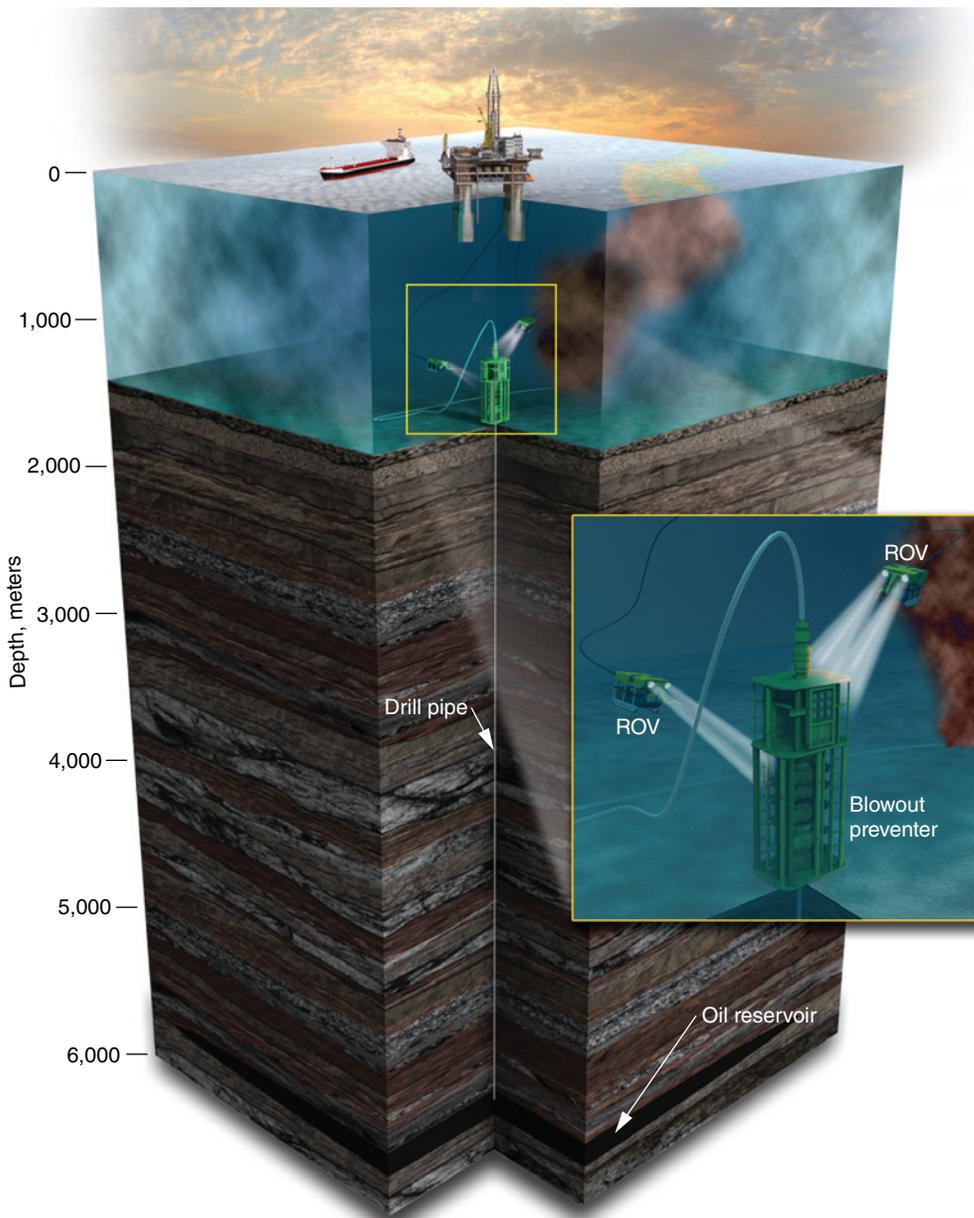
placing a 1×10^9 -becquerel source of cobalt-60 and a phosphor detector in water- and pressure-proof tubes. ROVs moved the detector and source into position underwater to image the valves in the device—the first time gamma-ray imaging had been successfully used at such a depth.

A Livermore team led by Maurice Aufderheide, a radiography expert in the Weapons and Complex Integration Principal Directorate, analyzed the resulting data. The team found that the preventer's internal valves were partially closed and somewhat restricting the flow of oil. Information from the imaging contributed to the decision to try sealing the leak with heavy drilling mud, an operation known as a "top kill."

When the top-kill operation failed, efforts turned to plugging the piping above the blowout preventer. This option, which proved successful, involved cutting the pipe and capping it. However, oil wells of this type are generally built with a number of nested pipes. Before the main pipe, or dogbone, could be cut, operators needed to know what was inside it.

The Los Alamos imaging team obtained radiographs of the bent, kinked dogbone, and analysis teams at Los Alamos and Livermore located interior drill pipes within it. As part of this effort, Ed Kokko, who works in Livermore's Engineering Directorate, converted a Sandia model of nested pipes into a model that used the Livermore hydrodynamics code ALE-3D. The conversion allowed Aufderheide to examine the images with HADES, a radiographic simulation code developed at Livermore. Aufderheide further analyzed the nested pipe geometries using models constructed with BRL-CAD, an open-source, computer-aided design system developed by the Army Research Laboratory.

BP also used acoustic scanning with commercial sensors to examine pipes and valves. Just as a doctor places a stethoscope on a patient, an ROV positioned a sensor against the piping at



This conceptual drawing shows the Macondo well, blowout preventer, and broken piping after the BP well exploded and the Deepwater Horizon drilling rig sank. BP's remotely operated vehicles (ROVs) were the sole source of real-time images from the underwater leak site and the primary devices for performing repair and containment work. (Rendering by Sabrina Fletcher.)

four points to “hear” what was going on inside the pipe just below the blowout preventer. “The three labs brought in experts to analyze those signals,” says Sharpe. “We were looking for loose or moving pieces of metal and seeking to understand the conditions at the blowout preventer.” Sean Lehman, Dave Chambers, and Karl Fisher, signal-processing experts in Livermore’s Engineering Directorate, analyzed the data to diagnose the condition inside that area of the well.

In an ideal situation, ROVs would place sensors on multiple spots around a pipe and produce measurements simultaneously. However, because of constraints on time and ROV availability, BP could acquire only a snapshot of acoustic data. Even with the limited data, the engineers confirmed that a loose piece of metal was floating inside the pipe. Lehman credits the Laboratory’s experience in processing raw signal and image data from various types of experiments with facilitating the imaging work at many stages of the oil-spill response.

For the modeling and analysis efforts, Livermore engineers and scientists worked in parallel with teams from Los Alamos and Sandia. Teams performed independently but sometimes discussed approaches during the process. Their results were then compared with those from BP’s analyses. “BP didn’t want us to just replicate their work,” says Livermore engineer Scott Perfect. “They wanted fresh eyes and independent calculations from the labs.”

Modeling a Giant Garden Hose

Another contribution by the three laboratories was to estimate the size of the Macondo well leak, using complementary techniques such as measurement, observation, particle velocimetry, fluid mechanics modeling, and imaging. Livermore engineer Diane Chinn led a team of image-processing and fluid mechanics experts who reviewed ROV-supplied images of the leak frame by frame



BP’s crisis command center in Houston, Texas, was called the HIVE because it offered a highly immersive visualization environment. From these consoles, command center staff controlled 40 to 60 ships and 12 to 16 ROVs during containment and oil-recovery operations. (Courtesy of BP PLC.)

and estimated the velocity of particles escaping the well.

Two other Livermore groups, one led by Roger Aines and Todd Weisgraber in conjunction with the National Energy Technology Laboratory and the other by Wayne Miller and Mark Havstad, performed independent fluids modeling and analysis to calculate the flow. Crisis response activities such as designing a cap for the well, predicting the extent to which oil would befoul Gulf wetlands, and determining how many ships were needed to collect oil depended on an accurate flow estimate from the leak. The measurement task, which would be quite straightforward on land, became an enormous challenge deep underwater.

According to Miller, a thermal fluids analyst in the Engineering Directorate, his group approached the flow-rate problem as if they were trying to determine the amount of water flowing from a garden hose that had a spigot at one end and a pressurized reservoir at the other. For this calculation, the team needed to know the size of the

“hose” (in this case, the well), the pressure inside it, and the physical properties (viscosity and resistance) of the medium flowing through it, whether water or oil.

Unfortunately, the oil well was not simply one pipe stretching deep into the subsurface. As with the piping above the blowout preventer, the well contained a series of concentric pipes and casings that provided support and enabled drilling operations. To calculate the oil pressure and flow rate, engineers needed to determine whether oil was flowing only through the central oil string, a pipe less than 25 centimeters in diameter, or between the various piping and casing components, a condition known as annular flow.

Several weeks before the explosion, BP engineers had measured the pressure in the oil reservoir, some 4,000 meters below the seafloor. At that time, it was about 83 megapascals, but the engineers knew it had dropped as oil continued to leak. Pressure at the entrance to the well pipe—a key area for creating an accurate flow model—depended on the quantity

of reservoir sediments that the oil was flowing through to reach the pipe. During the early calculations, the pressure at the top of the well was also uncertain. Readings from the original gauge on the blowout preventer were suspect and eventually found to be inaccurate.

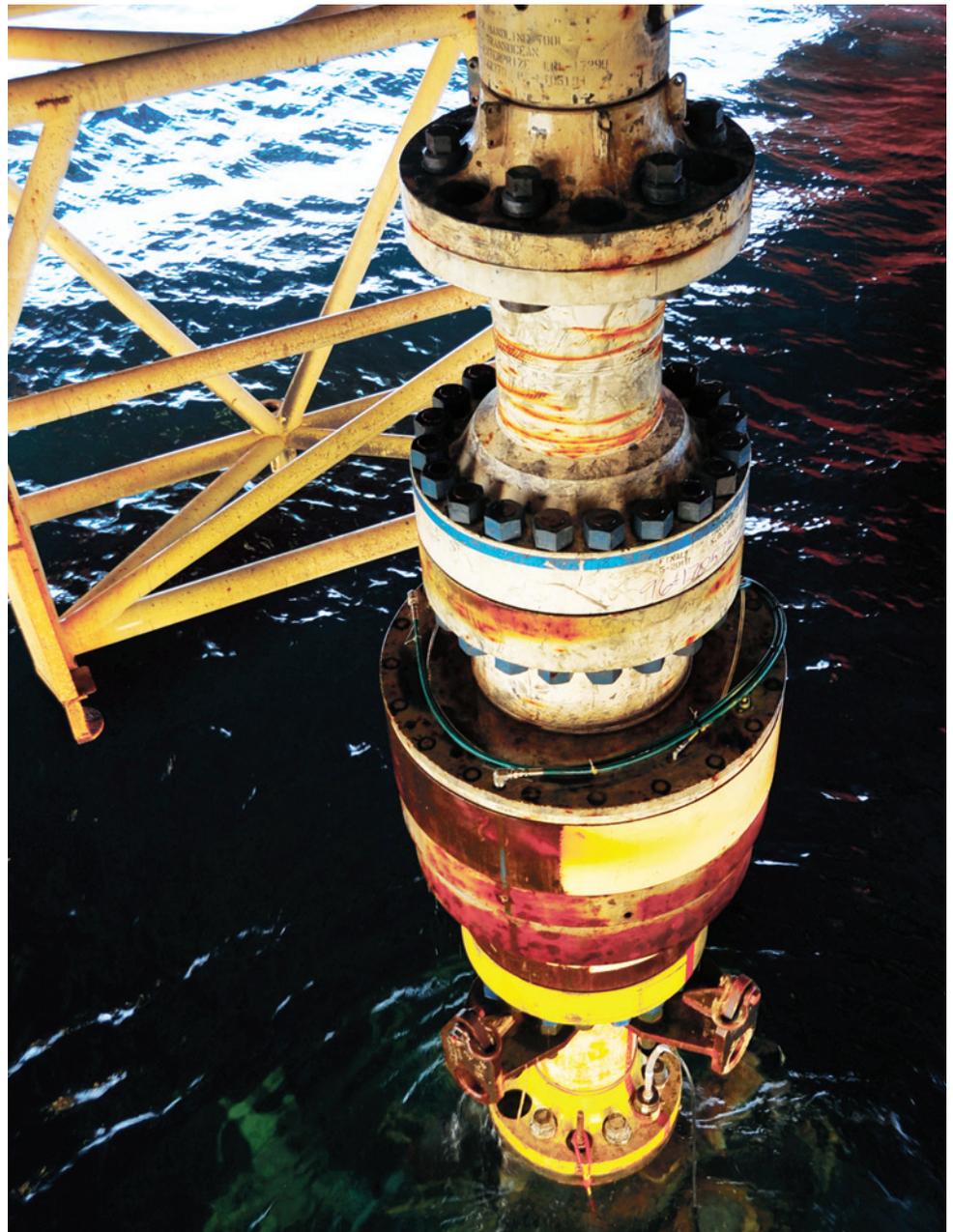
Complicating the calculations were the oil's physical properties. Deep underground, oil is hot and full of emulsified gas, a viscous mixture that Miller compares to carbonated water under pressure. As hot oil rises through the well and contacts the nearly freezing seawater, it cools, and its pressure gradually drops. In addition, the gas begins to bubble and separate from the liquid. Accounting for these two changing phases of material complicates calculations of oil density and flow rate.

In June, ROVs sliced off the bent pipe and installed piping to transport the escaping oil to the surface for collection. During this procedure, BP attached several pressure gauges to the new structure, to more accurately measure the pressure at the blowout preventer and the surface. Although engineers could now better understand the current pressure and flow rate, they still had to determine the past rate and the total overall because flow had not been constant. In fact, installing new structures, such as the oil-collection piping, increased the total pressure in the system.

At the same time, the reservoir was gradually being depleted, which reduced the pressure of oil entering the well

and piping. The U.S. Geological Survey estimated that pressure dropped from 83 to 34 megapascals during the three-month leak. Researchers now project that the flow rate decreased from 10,000 to 8,400 cubic meters (63,000 to 53,000 barrels) of oil a day over the duration of the spill, as the well was depleted and new structures were attached to the blowout preventer.

Engineers from the three laboratories developed estimates independently, refining calculations over time and adding new information as it became available. Ultimately, their results agreed within 10 percent. "We didn't have the luxury of writing journal articles," says Miller. "We needed quick, practical solutions, so we had to make flow calculations with incomplete information."



The damaged blowout preventer was eventually removed from the well and replaced. The 20-meter-high device, shown here as it is lifted aboard a ship, will be examined to better understand the events leading up to the oil leak. (Courtesy of U.S. Coast Guard.)

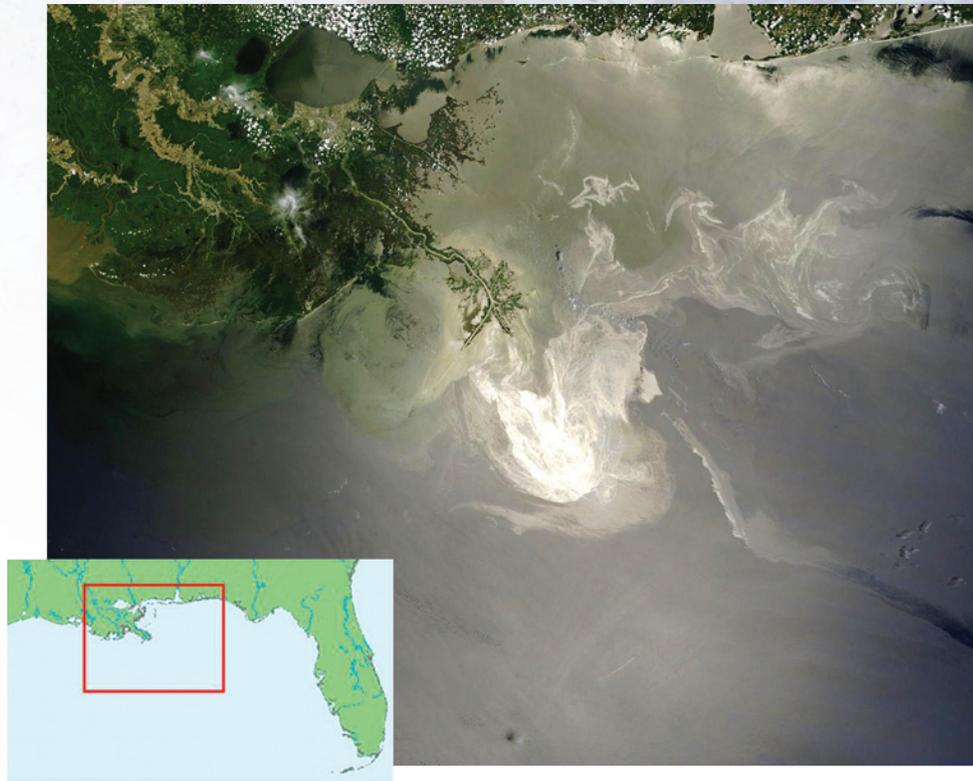
Preparing for the Next Crisis

The largest accidental spill in the history of the petroleum industry has been stopped, although environmental assessment and remediation continue in much of the Gulf. Many scientists and policy makers are now focused on preventing future disasters of this magnitude. Having received a crash course in oil-drilling technology, Laboratory engineers have had an opportunity to consider methods that might improve the safety of fossil-fuel exploration and drilling operations. Suggestions include deploying more in situ diagnostic techniques, adding layers of safety with standardized and certified hardware, and modifying equipment and technologies to operate in harsh environments, for example, building faster, more dexterous ROVs.

Several participants noted that the national laboratories would be an excellent resource in developing relevant technology. For example, Lehman's group has expertise in building "smart parts," integrating acoustic, electromagnetic, and other sensors into equipment or a structure (say, an engine or bridge), to monitor its "health"—usage, wear, and deterioration that might affect its safety or reliability. Perhaps in the future, the Laboratory could be engaged to design "smart" blowout preventers.

Supporting BP during the crisis also led Livermore engineers and scientists to consider their broader role in preparing for and responding to national emergencies. "The next crisis won't be an oil spill," says Perfect. "The question is how do we, as national labs, set up for a quick response, whatever the emergency might be. If we are called on, we need to be ready." To that end, groups within the Engineering Directorate are doing best-practice exercises to assess the effectiveness of their procedures and ensure that they can promptly provide the technical expertise to address an unknown scenario.

In responding to the disaster, scientists and engineers from Livermore, Sandia, and Los Alamos also had a chance to build relationships with technical experts



On May 24, 2010, the Terra satellite captured sunlight illuminating the growing oil slick off the Mississippi Delta. (Courtesy of National Aeronautics and Space Administration.)

and government agencies outside their research communities and professional networks. Sharpe notes that, despite initial skepticism, BP came to value the technical competence and alternative viewpoints offered by the staff from the national laboratories. "Part of what made us effective is that although most of us knew little about the oil industry," says Perfect, "we're good problem solvers." The broad interdisciplinary experience of national laboratory researchers allowed them to respond quickly and provide measurable support to a large, complex effort.

For participants, the experience was unique. "Many aspects of the crisis response were quite different from our normal operating environment," says Aufderheide. "Working in this unusual

setting has given us a chance to improve our craft for future efforts." Adds Warner, "It's not often that we get to see our work on television every day. We played a supporting role, but an important one."

—Rose Hansen

The views and opinions expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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For further information contact Rob Sharpe (925) 422-0581 (sharpe1@llnl.gov).