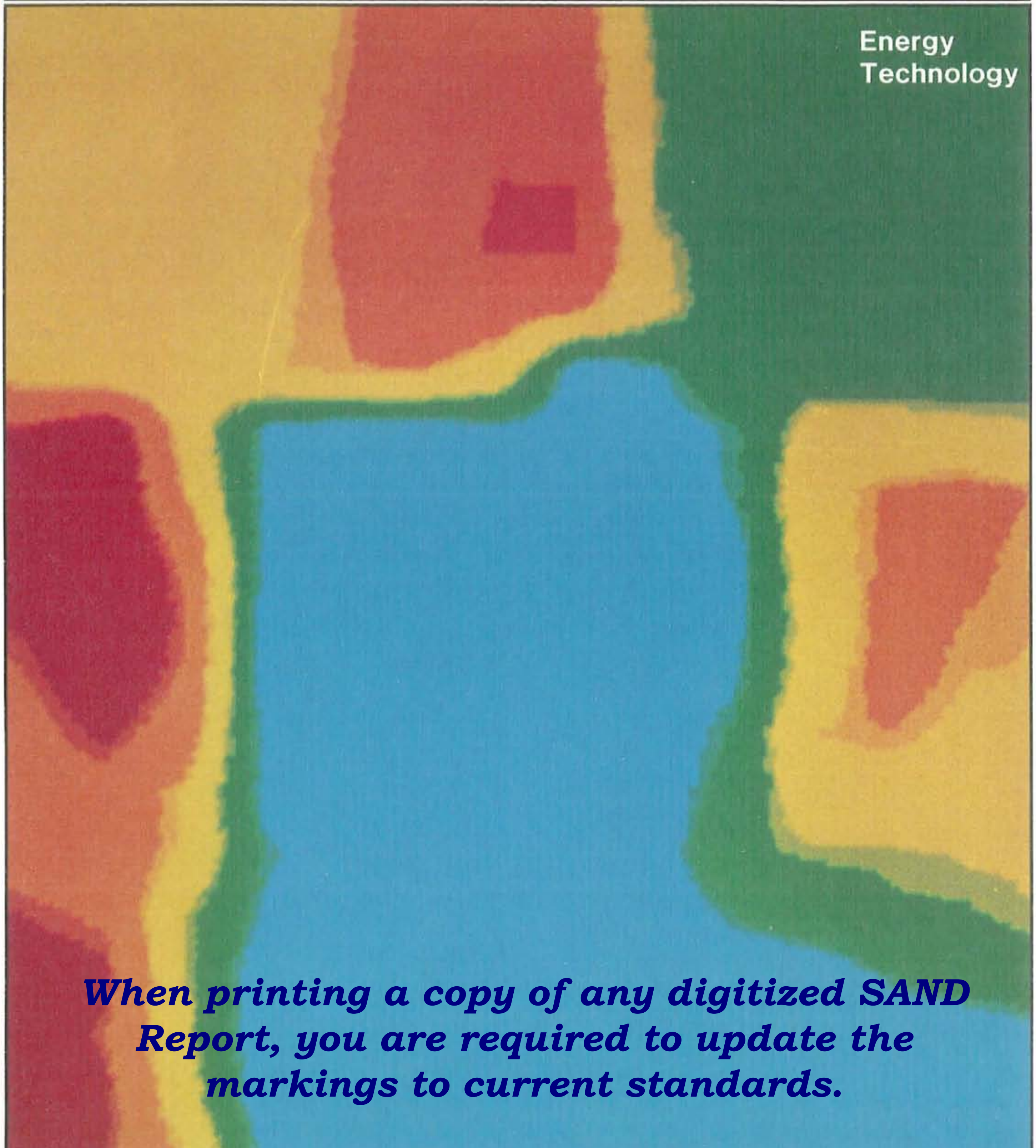
SAND86-1514

SANDIA TECHNOLOGY

Energy Technology



Sandia National Laboratories, Albuquerque, New Mexico/Livermore, California/Tonopah, Nevada

◀ **Cover Photo:**
Temperature contour plots and other data from Sandia instrumentation were used to evaluate an in situ burn of rubblized oil shale at an Occidental Oil Shale, Inc., site near Debeque, Colorado **(see page 9).**

Sandia Technology is published to meet a continuing responsibility to inform the taxpayer—who ultimately funds our work—about Sandia's technical activities. It also is intended to facilitate the transfer of technology to industry and universities.

SAND 86-1514
Vol. 11, No. 1

SANDIA TECHNOLOGY

April 1987

Sandia National Laboratories

CONTENTS

Published by
Management Staff, 400
A. N. Blackwell, Director

Supervising Editor
A. D. Thornbrough

Scientific Editors
B. M. Butcher
J. F. Calek
M. L. Merritt

Publication Editor
D. S. Rix

Art Director
K. R. Miller

For information
about Sandia Technology contact:

Publication Coordinator
Sherrye T. Lavasek
(505) 844-4958

For information
about technology transfer contact:

Technology Transfer Manager
G. W. Kuswa
(505) 846-4945

Sandia National Laboratories

Sandia is a multiprogram laboratory operated for the Department of Energy with major facilities at Albuquerque, NM, and Livermore, CA, and a test range near Tonopah, NV. Our primary responsibilities are research and development of nuclear weapon systems from concept to retirement. We also have extensive responsibilities in other areas of national importance that are related to our primary mission. These include fusion energy, reactor safety, nuclear safeguards, energy research, microelectronics, and other undertakings that exploit our research and development capabilities. Our technological activities and accomplishments are reported in two corporate publications. Unclassified articles appear in ***Sandia Technology.*** Classified work is reported in ***Sandia Weapon Review***.

Fossil Energy

A Special Issue on Energy Technology

During the energy crisis of the early I970s, we were asked to direct our research and development resources to the problem of maintaining national energy security. We responded with enthusiasm and assembled an array of energy research programs that would complement or take advantage of technical capabilities originally developed for weapon programs. During 15 years of productive energy research, we have focused our efforts on developing technical means for reducing the nation's dependence on foreign oil.

Changing circumstances in the international oil market, the inclination of Middle East nations to use oil for economic influence, and declining domestic oil reserves have encouraged the substitution of other energy forms for imported oil. Certainly, coal will play a more important role as a source of energy over the next decade, particularly in the large scale generation of electricity. Moreover, political and economic consequences of the energy crisis have stimulated interest in developing efficient processes for converting coal to gaseous and liquid fuels. The steady decline in domestic oil and gas reserves has also prompted a search for new technologies to enable industry to recover more of these resources from known reserves and to tap less accessible deposits.

In this issue of **Sandia Technology**, we review our programs and technical developments for coal, oil, and gas. Our coal research program emphasizes advanced pretreatment and combustion processes to make the use of coal more environmentally acceptable. Our gas research program has focused on developing technology to aid in unlocking unconventional gas resources. We also review our work on renewable energy sources and electrical energy storage. Other energy related program efforts such as combustion science, nuclear reactor safety, and nuclear waste disposal have been or will be discussed in other **Sandia Technology** issues.

The variety of these energy related activities is evidence that we place high priority on ensuring a stable, safe supply of energy. I feel strongly that a continuing and vigorous national research effort is needed, particularly in advanced coal technologies and geosciences, to moderate the effects of an energy crisis that will surely occur within a decade. Beyond these immediate programs, we will continue to focus our attention on those high-risk but high-payoff technologies that will fulfill additional capacity requirements beyond the year 2000 and at the same time alleviate environmental pressures that will surely accompany our increased use of coal.

Irwin Welber

I. Welber
President

Fossil fuels, our country's most abundant resource, are expected to supply the greater part of the nation's heat, fuel, and electricity until well into the 21st century. US coal reserves, for instance, are estimated to be sufficient for 400 years. Oil and gas reserves, on the other hand, have declined steadily since 1970, indicating that national reserves in 2020 could be as low as 25% of the present level (Figure 1).

At Sandia, we are doing research and development work in all areas of fossil energy—coal, oil, and gas—and are active in developing advanced "cross-cutting" technology that applies to one or all of these areas. In the case of coal, we are experimenting with new pretreatment techniques, advanced conversion methods based on new and improved catalysts, and advanced combustion technology, all of which will be needed to achieve environmentally acceptable, efficiently transportable energy forms.

For oil and gas extraction, we are developing new technologies that will enable industry to obtain more of these resources from known reserves and to tap less accessible deposits at affordable costs. This will reduce US dependence on foreign imports and help offset an energy shortfall that is projected to begin in the 1990s.

Coal

Coal is an abundant resource in the US, with most estimates indicating a few hundred years'

We are developing new technologies that will enable industry to obtain more oil and gas from known reserves, to tap less-accessible deposits at commercially feasible costs, and to use unconventional techniques such as oil-shale retorting and coal liquefaction.

supply. It is used almost entirely as a solid fuel for boilers in industrial and power-plant applications. It accounts for about 23% of our total energy usage and is the only net US energy export. Innovative new processes such as gasification — both surface and underground — and liquefaction will be required, along with improved clean-coal technology, to fully integrate coal into our future energy picture.

Coal Liquefaction

If we are to take advantage of our abundance of coal to supplant petroleum for our liquid-fuel requirements, catalytic processing will be essential for any efficient conversion process. Use of catalysts is necessary to liquefy coal economically by the addition of hydrogen and to remove potentially polluting elements such as sulfur and nitrogen. However, currently available catalysts developed specifically for petroleum feedstocks are not optimal for processing coal. Our catalyst research program is focused on exploring novel catalysts for coal-liquefaction processes and determining the causes of rapid catalyst deactivation — currently a major economic impediment to the production of liquid fuels from coal.

We have identified a group of hydrous metal-oxide ion exchange compounds that can be used to synthesize catalysts (Figure 2). Initial tests demonstrated that these catalysts, containing only 1/10 the amount of active metals of currently available catalysts, are very effective for liquefying coal. Hydrous metal-oxide ion-exchange catalysts, because of their high activity, allow us to carry out solvent hydrogenation at reduced temperature and pressure, improve product selectivity, and explore new concepts for advanced coal-liquefaction processes.

Analyses and modeling of deactivation of catalyst samples retrieved from the DOE Liquefaction Process Test Facility at Wilsonville, Alabama, have shown how important a problem rapid catalyst deactivation is: half of catalyst activity is lost within one day of coal processing. Modeling has allowed us to determine mechanisms of deactivation by carbonaceous and metallic contaminants. Research is continuing to identify and eliminate the chemical sources of contaminants and thus improve catalyst life and process economics. A new, simplified coal liquefaction process has been developed that is designed to operate without purified hydrogen. The new technique, which operates at considerably lower pressures and temperatures than present-day liquefaction designs, could lead to significant cost savings. A key to this work is the recognition that there are two paths to liquefaction—thermal and catalytic—and that, in contrast to

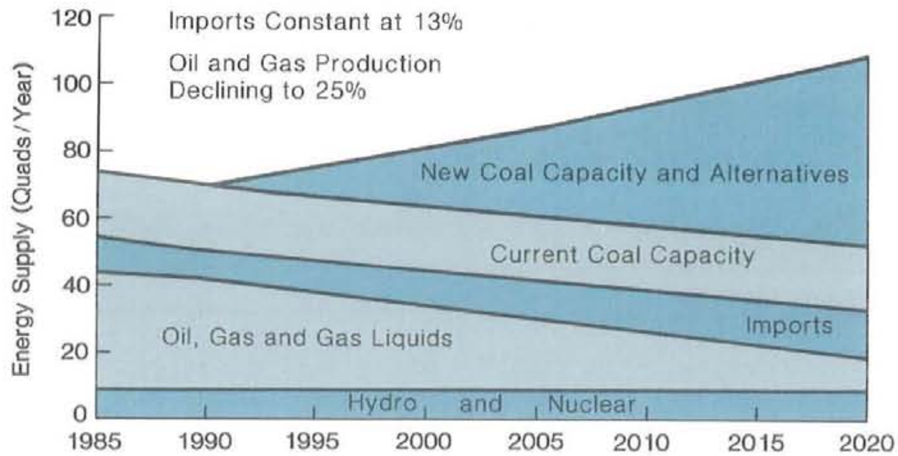
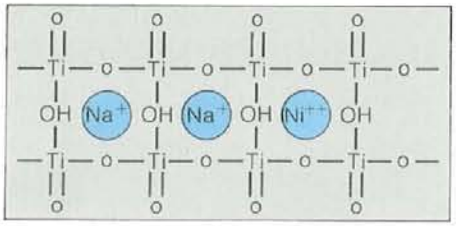
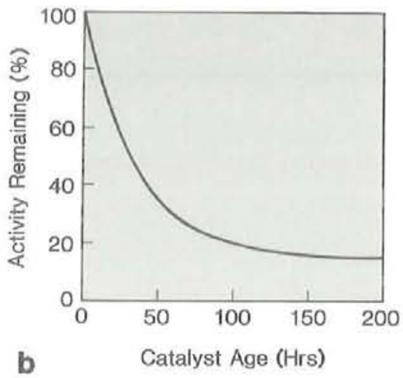


Figure 1
If energy imports continue to be limited to 13% of our total consumption, and US oil and gas production are assumed to decline to 25% of the 1985 level by 2020, major requirements for new coal capacity or other alternatives will emerge by 1990. If imports increase to 24%, the need for new capacity or alternatives remains but is delayed until 1995.



a



b

Figure 2
Novel catalysts (a), formed by a hydrous metal-oxide ion-exchange process offer less severe operating conditions, better product selectivity, and more efficient processes. Coal-liquefaction catalysts deactivate rapidly (b). Our research seeks to identify deactivation mechanisms and eliminate deactivating compounds, thus improving catalyst life and process economics.

the thermal path, the catalytic steps are most efficient at low temperatures and pressures (Figure 3).

A new program uses computer-aided design and interactive molecular graphics to formulate catalysts. Efforts are underway to develop shape-selective materials for the direct conversion of methane to methanol. These catalysts are thought to contain pockets or cavities where the reactions of interest can take place. In this way, they will mimic the actions of naturally occurring enzymes that can catalyze the direct conversion of methane to alcohols and other chemicals.

One of our achievements is the design, development, and testing of the helical-screw rheometer to measure fluid viscosity under difficult conditions of high pressure and temperature (Figure 4).* We have used the device to study physical changes that take place as coal is transformed to a liquid and formation of stable coal-water slurries. Studies of the behavior of atomized slurries are also underway. A number of manufacturers are interested in the new rheometer and are receiving design guidance from us.

*See "The Helical Screw Rheometer," *Sandia Technology, Vol. 9, No. 3,* August 1985.

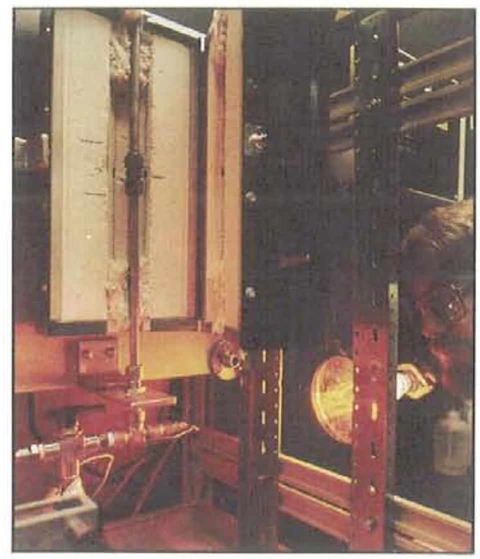


Figure 3
A microreactor is used to measure the activity of coal-liquefaction catalysts. These tests help us determine the effects of sulfur and nitrogen on the life of a catalyst.

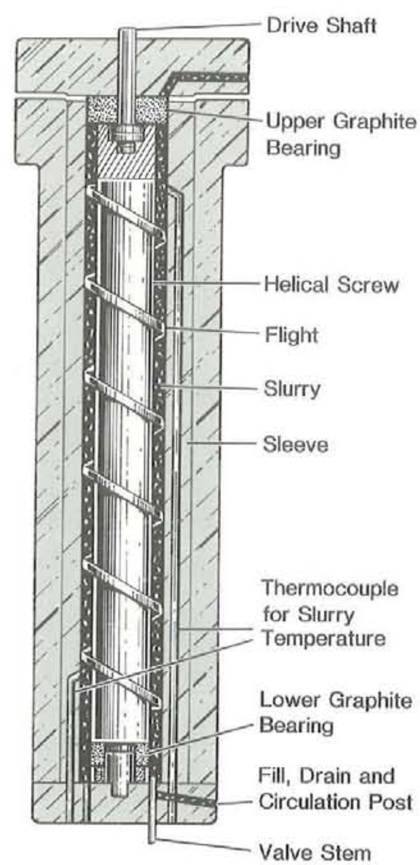


Figure 4
The helical-screw rheometer, developed at Sandia, measures fluid viscosity under difficult conditions of high pressure and temperature. The device's name derives from its design: a rotating helical screw that generates the flow necessary to allow measurement of viscosity.

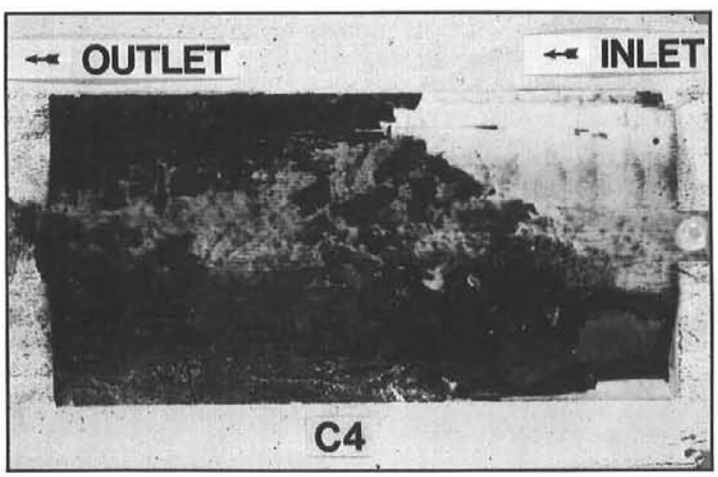
Underground Coal Gasification (UCG)

Basically, UCG is a process in which wells are drilled into a coal bed. Air or an oxygen/steam combination is then injected to support controlled burning, and product gas (mixed hydrogen, carbon monoxide, carbon dioxide, and methane) is withdrawn from neighboring wells that are usually linked to the injection well by a horizontal borehole. Important advantages of the in situ process are that neither mining of the resource nor surface disposal of waste products is necessary.

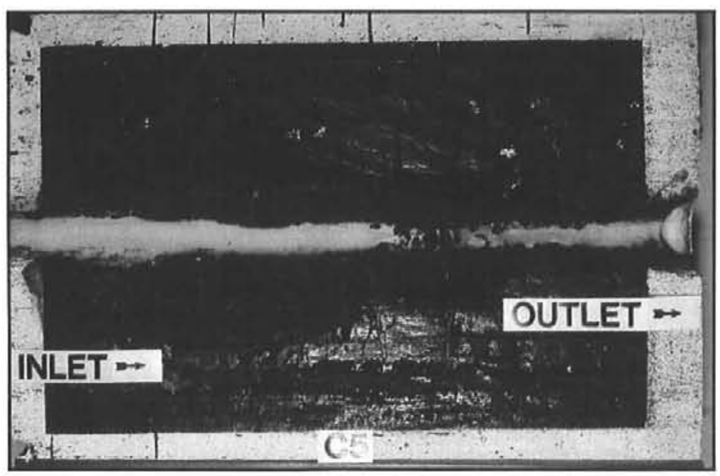
We began working on UCG in 1974, primarily in an area in which we are particularly strong — underground instrumentation. At that time, very little was known about the shape and growth of in situ combustion regimes. In a field experiment near Hanna, Wyoming, we applied both direct thermal and remote-sensing techniques to monitor the process. Thermal instrumentation was particularly successful in delineating key features of process geometry. We demonstrated, for example, that reverse combustion (where burning goes in the opposite direction from air flow) is a multipath phenomenon that follows natural fractures in the coal.

At the same time, we initiated a modeling effort to examine the effect of mechanical properties of the coal on the shape of the developing gasification cavity. The models demonstrated that thermo-mechanical effects could account for different cavity shapes in different coals. We also developed advanced thermal instrumentation to telemeter data from beneath a burn zone. This instrumentation provided unique data on cavity formation.

Since 1984, our efforts have been directed to applying UCG technology developed on western sub-bituminous coals to eastern bituminous coals (Figure 5). Interest in eastern coal is stimulated by its estimated 100-year supply and by the fact that it is relatively close to heavily populated industrial end-use areas. However, these coals have characteristics that pose problems in developing an effective UCG process; these include swelling, tar production, and low-reactivity, high-strength char. Eastern coal also contains high sulfur fractions, and some is located in seams too deep or beds too thin for mining, probably requiring unconventional extraction methods. Laboratory gasification tests, with supporting modeling studies, are being conducted on an Illinois coal. Procedures for processing bituminous coal in an open borehole have been developed. This work will lead to tests of gasification concepts appropriate for bituminous coals.



a



b

Figure 5
Our laboratory tests show important differences in gasifying western sub-bituminous (a) and eastern bituminous coals (b). Developing a successful field process for the eastern coals will prove challenging.

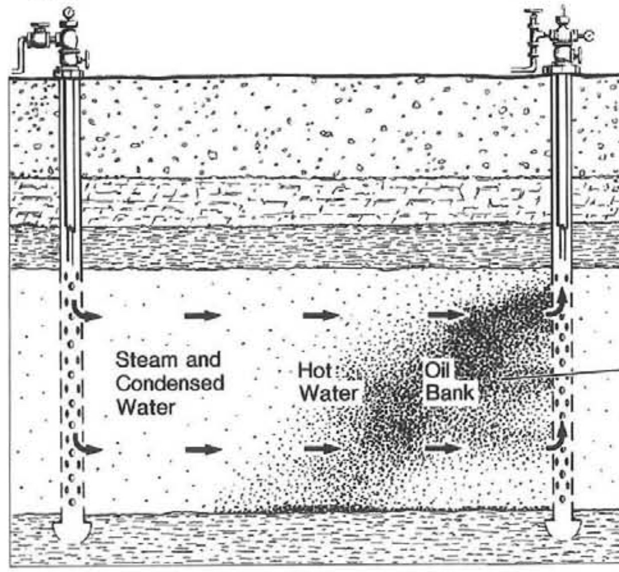


Figure 6
Injection of steam into a formation from a boiler on the surface is the most widely used method of extracting heavy oil. Steam entering the formation reduces oil viscosity and provides a moving water front that forces the oil toward a producing well.

Oil

Liquid fuels (petroleum) furnish about 42% of the energy used in this country, with a substantial portion (about 30%) of that imported. Proven US reserves continue to decline; no truly significant new field has been added since the Prudhoe Bay discovery in 1970. Expanded use of enhanced oil-recovery (EOR) techniques caused an interruption of this downward trend during 1985, but long-term forecasts suggest that proven reserves could decrease to 25% of the 1985 level by 2020. As a result, increased use of present EOR techniques and introduction of advanced ones will be needed. This shortfall will also place increased importance on development of methods to extract "unconventional" oil — for example, shale oil.

In our EOR work we have emphasized both improved efficiency for conventional thermal extraction and development of new technology to extend thermal methods to deeper reservoirs. Our oil-shale work has been devoted to in situ processes: we have provided extensive instrumentation to establish a data base for field retort operations and have developed better understanding of fragmentation, rubblization, and retorting through field experiments and improved modeling.

Enhanced Oil Recovery

The objective of our Project Deep Steam was to develop technology for more efficient removal of heavy oil from shallow (<800-m) deposits and to permit extraction from deeper reservoirs. We used two approaches: thermally efficient delivery systems for surface steam generators, and development of downhole steam generators.

Heating by steam injection is the most common method of extracting heavy oil — the kind with a consistency like molasses. Steam is continuously injected into the reservoir to lower the viscosity of the oil, a method known as "steam flooding" or "steam drive" (Figure 6). Pressure from the steam and condensed water forces the heated oil toward the production well where it can be pumped to the surface.

Steam flooding may also prove useful for extracting oil still remaining in depleted light (low-viscosity) oilfields. A typical oilfield produces only a third of the oil in its reservoir because the rest is trapped in the pores of hard-to reach geologic formations.

Until the late 1970s, steam was pumped downhole through bare pipe in most fields. These fields were generally in southern California, where oil deposits lie 150 to 425 m below the surface. Heat-loss rates were high, so the steam cooled before it reached the oil, but because fuel costs were low, producers accepted the inefficiencies. Later, as energy costs rose, producers began using insulated tubing to get more heat into the oil formation, particularly as production from deeper reservoirs became more important.

In the early 1980s, we set up a program with Husky Oil Company to measure the long-term performance and efficiency of insulated tubing in an operating oilfield. Experimenting with commercial tubing, we discovered that heat losses were much higher than predicted. We suggested that the problem was "wellbore refluxing" — the loss of energy into the earth through uninsulated parts of the injection string, including steel couplings between insulated tube sections (Figure 7). We proposed two methods for eliminating refluxing: 1) remove moisture from the casing annulus and 2) insulate the tubing couplings.

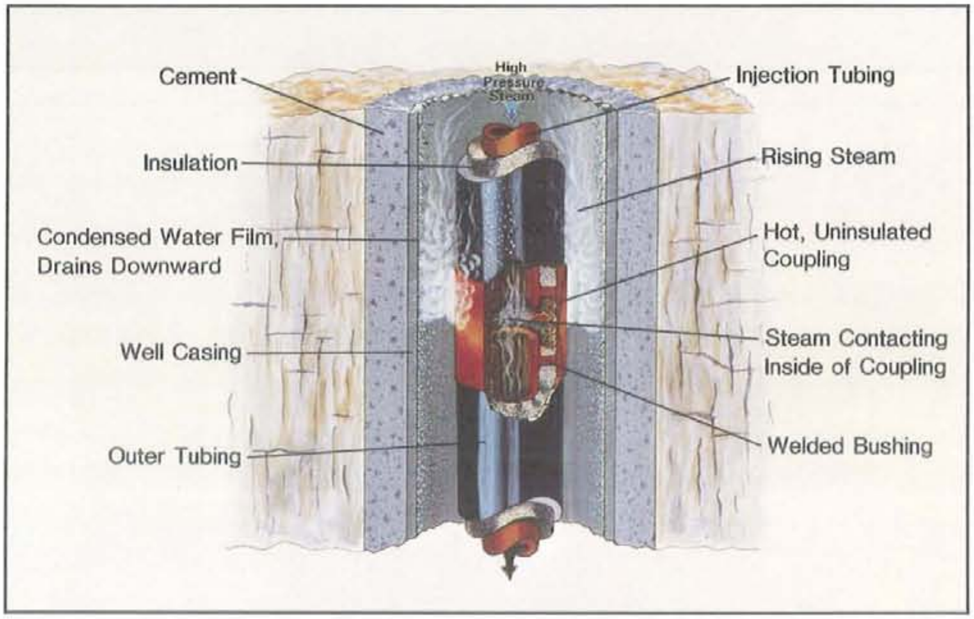


Figure 7
Refluxing is a heat-pipe process that results in the undesirable cooling of steam on its way downhole. When moisture contacts the outer surface of uninsulated hot couplings, it flashes to steam. The steam rises up the wellbore and condenses on the relatively cold well casing, giving up its heat to the surrounding rock formation. The condensed water then trickles down the casing until it again comes in contact with a hot coupling and the cycle repeats.

Since pumping water liquids and vapors from the tubing-casing annulus is not economic, we limited our work to the second method. We placed a ring of insulation around the inside wall of the coupling (Figure 8). When the joint is screwed together, the insulation is squeezed to fill the void in the coupling, thus keeping steam in the tubing from contacting the outer walls. Laboratory tests in a 37-m wellbore showed that this provides enough insulation to keep water in the wellbore from vaporizing when it contacts the couplings.

We conveyed these findings to the manufacturers of insulated tubing, and many are now providing insulated couplings in their product. We estimate that the use of insulated couplings can result in energy savings of over $1 billion in the next decade. DOE invested less than $2 million in the program.

An alternative to producing steam on the surface and injecting it downhole to the reservoir is to produce it directly in the oil formation by means of a downhole steam generator (see Box A). This technique precludes wellbore heat losses and makes it possible to extend thermal stimulation to oil deposits at depths greater than presently attainable (about 750 m).

There is also reason to believe that the effects of steam mixed with combustion exhaust gases will cause more rapid increases in oil production than those from steam alone.

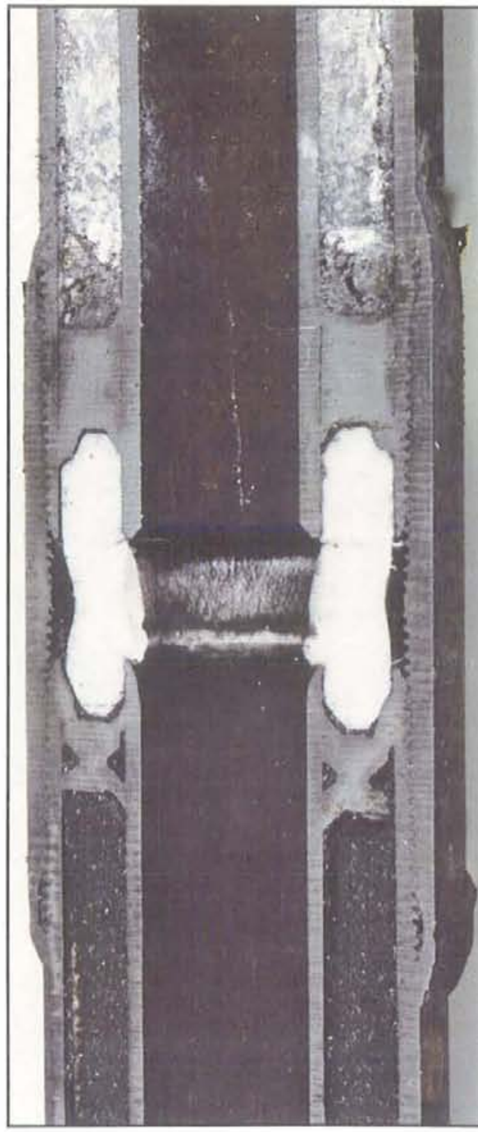


Figure 8
Sandia-designed insulation that fits around the inside wall of the coupling eliminates the refluxing problem. When the coupling is tightened, the ring expands to provide a tight, insulating seal. Insulated-tubing manufacturers are incorporating this technology into their products.

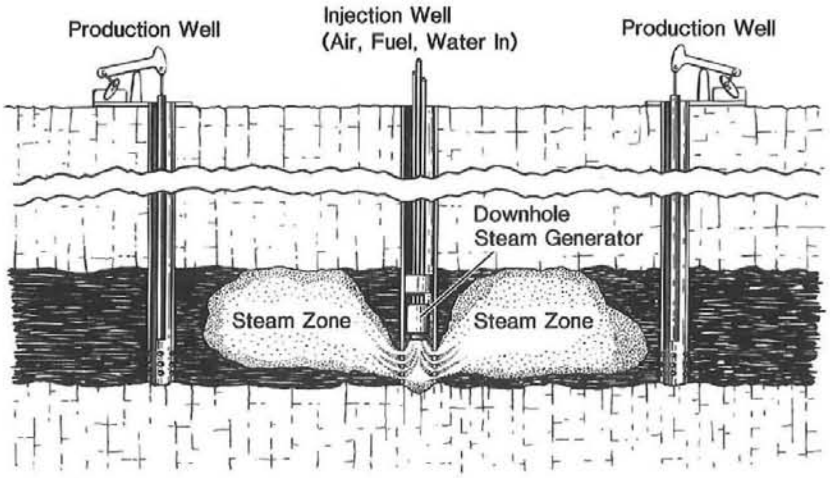
BOX A

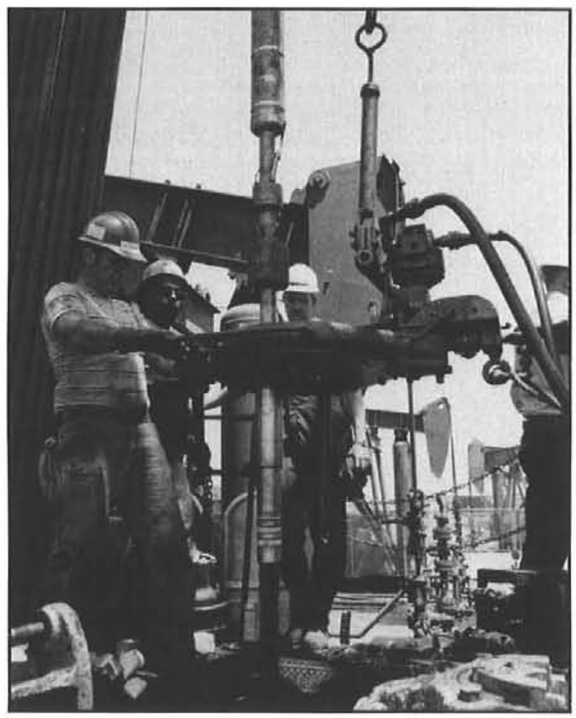
Downhole Steam Generation

We began our downhole-steam-generator project in the late 1970s with a broad-based technology selection and development effort and completed it in 1982 with a 9-month field evaluation in the Wilmington Field at Long Beach, California. In the final field test, we placed two high-pressure combustors and steam-generating devices in adjoining patterns of existing oil wells; one burned diesel in air and was placed at a depth of about 670 m, while the other burned diesel in pure oxygen and was located on the surface. Both units injected their energy in the middle of near-rectangular plots that had existing oil production wells on the corners. We instrumented both units extensively. After several months of operation, we concluded that the monitoring and control concept for downhole operation is satisfactory. Having discovered certain metallurgical and thermal stress conditions in the walls of the combustor, we ran laboratory studies in these areas and now feel we understand how to avoid similar problems in future designs.

We measured production-gas temperatures and compositions while maintaining a record of production rates from the surrounding wells. Combustion gases were detected in all sampled wells, and periods of increased or decreased levels were correlated with system operation. In one well a sharp increase in produced-gas temperature, together with an increase in the oil-production rate, was taken as evidence that the steam generator was reaching out into the surrounding reservoir and causing increased oil movement. These results, combined with other considerations, induced the operator to install a commercial downhole steam generator in this well following completion of our program.

In general, downhole steam generators are as yet less proven and more costly than other EOR techniques such as surface steam injection, CO_2 injection, and chemical additives. However, the technology can enhance oil extraction, particularly in deeper formations, and will become useful as economic considerations change and further development occurs.




Inserting the downhole steam generator

Oil Shale

Huge quantities of oil in the form of kerogen are entrapped in extensive formations of finely layered brown or black shale in both eastern and western mountains. Both in situ and surface processing methods have been proposed for extraction of this resource, but neither has proven economically feasible to date. Surface processing — in which mined shale is brought to the surface for crushing and retorting — has received the majority of industry and government support. Our work has centered on the in situ process, in which air is pumped down to the formation and part of the in situ hydrocarbon is consumed to free other liquids and gases for production.

Jointly with Occidental Oil Shale, Inc., we instrumented and analyzed extensively two large in situ retorts near Debeque, Colorado (Figure 9). Occidental explosively rubblized about 450,000 tonnes of shale,

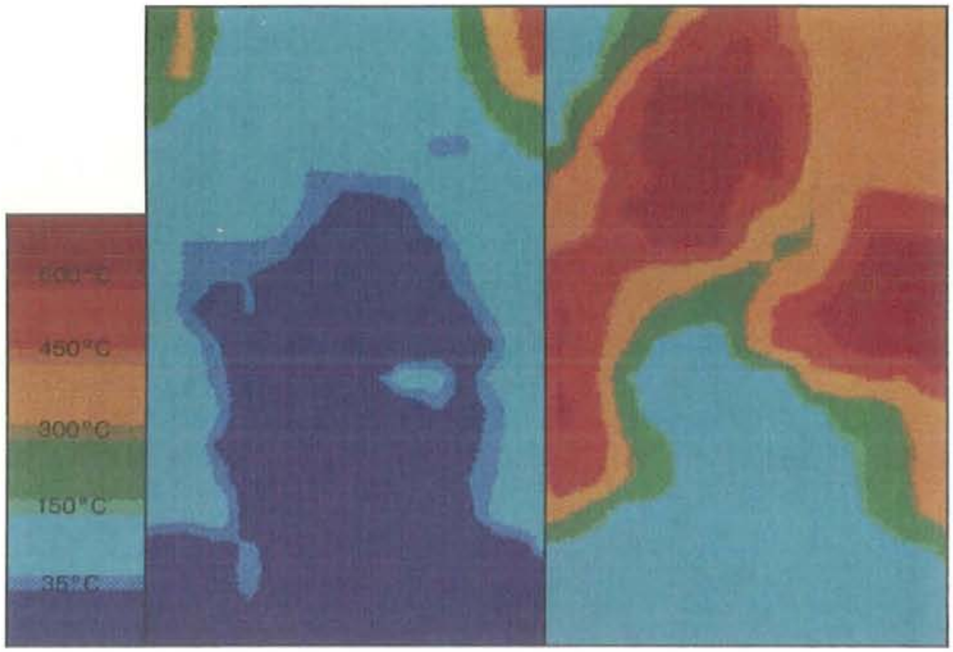
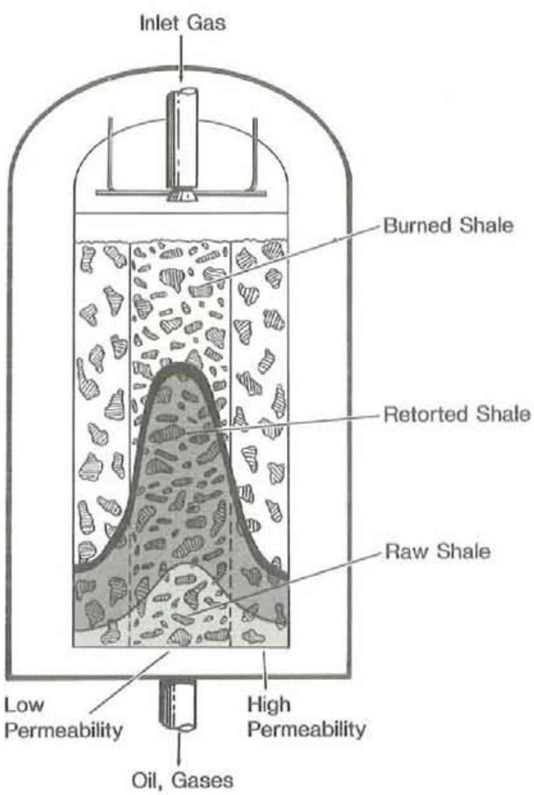


Figure 9
We collaborated with Occidental Oil Shale, Inc., in instrumenting and analyzing two large in situ retorts near Debeque, Colorado. Occidental explosively rubblized and retorted shale containing over 150,000 bbls of oil per retort. Data such as these temperature contour plots provided the basis for evaluating the process.



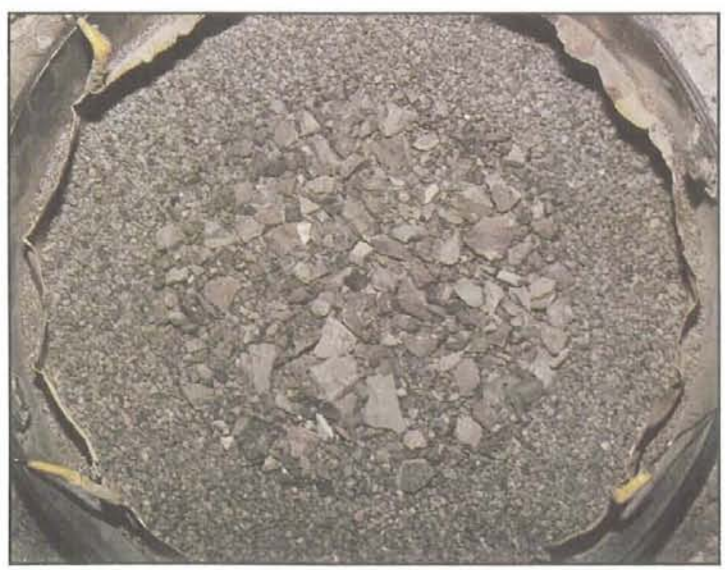


Figure 10
In laboratory experiments on oil shale, we examine the effects of nonuniform rubble on retort performance. The tests provide information on local yield loss, oxygen-consumption patterns, rubble/competent-shale interfaces, and horizontal versus vertical retorting.

Figure 11
Before and after a blasting experiment in an oil-shale mine at Anvil Points, Colorado. The explosives are in boreholes below the surface. Instrumentation includes high-speed cameras to monitor motion (red-and-white flags), in situ stress and acceleration gauges to monitor ground motion, and timing measurements on the explosives.

containing some 150,000 bbls of oil in each of the two retorts. We installed over 1000 instruments (thermocouples, pressure gages, gas analyzers) and obtained data for over 300 days of processing. Our analysis indicated that the average yield was about 57% of the available oil for both retorts (including oil used for combustion). We also determined that another 10-20% may be obtained in a future design by condensing the light hydrocarbons in the retort gas. Our data showed the effects of nonuniform rubble in the retorts, and we have identified this nonuniformity as a major cause of yield loss for in situ processes.

Through analytical and laboratory research, we are defining the effects of permeability variations on the efficiency of oil-shale retorting (Figure 10). Beds of controlled permeability contrasts are retorted. Flow rates, chemical composition, temperatures, and pressures are monitored throughout the bed. Experimental results are then used to improve analytical models.

In addition to understanding chemical and physical processes, we must be able to design blasting systems to optimize permeability distribution. Analytical codes are being developed to couple initial shock-wave interactions with subsequent fracture openings and rock motion. The analytical work is supported by both laboratory and field-scale blasting experiments, the latter being necessary to take into account effects of heterogeneity in shale beds (Figure 11). Results to date show correlation between codes and experiments adequate for rough engineering designs.

As with some other fossil-fuel and solar technologies, the cost of processing oil shale is not presently competitive. Estimates based on current oil-shale technology place costs at four times recent oil prices or more. Improved second-generation technology that we are developing can increase efficiency and reduce costs, but these improvements are not likely to make oil-shale retorting commercially feasible as long as today's energy situation exists. Nevertheless, the magnitude of the US resource, plus limited reserves of conventional oil, imply that oil shale will have a place in our future energy-supply picture.

Enhanced Gas Extraction

In this program, we develop technology to aid in unlocking the nation's unconventional gas resources. These include tight gas sands (whose permeability is orders of magnitude lower than concrete) and Devonian shales, which underlie much of the eastern US. Recoverable gas from these sources is estimated to be several hundred trillion ($10^{13}m^3$) cubic feet (tcf); current annual gas consumption is 17 tcf ($5 \times 10^{11}m^3$).

Reservoir stimulation (fracturing) of some kind will be required in each case to increase gas flow to a wellbore. Historically, two fracturing methods have been used: hydraulic (the most common) and explosive. In the former, fluid is pumped into the formation and fracturing proceeds slowly as volume and pressure are increased. A single fracture plane up to 1,000 m in length is sometimes produced. Explosive fracturing has limited range (less than 20 m) and in many cases has resulted in a crushed, compacted zone near the wellbore that actually reduces local permeability.

We have been conducting fracturing experiments in a deep tunnel at DOE's Nevada Test Site (Figure 12). In these experiments, we can instrument and subsequently uncover and observe the fractures by mineback operations (Figure 13). We have shown that growth of these hydraulic fractures is controlled by in situ stresses, a concept now used in daily industry practice. We have instrumented a hydraulic fracture to obtain width and pressure away from the wellbore during fracturing. This test, a first, provided valuable new information on fluid flow and fracture properties. Also, we can examine the effects of common engineering practice upon fluid flow, such as perforation (where holes are shot in the well's casing to open the well to the reservoir).

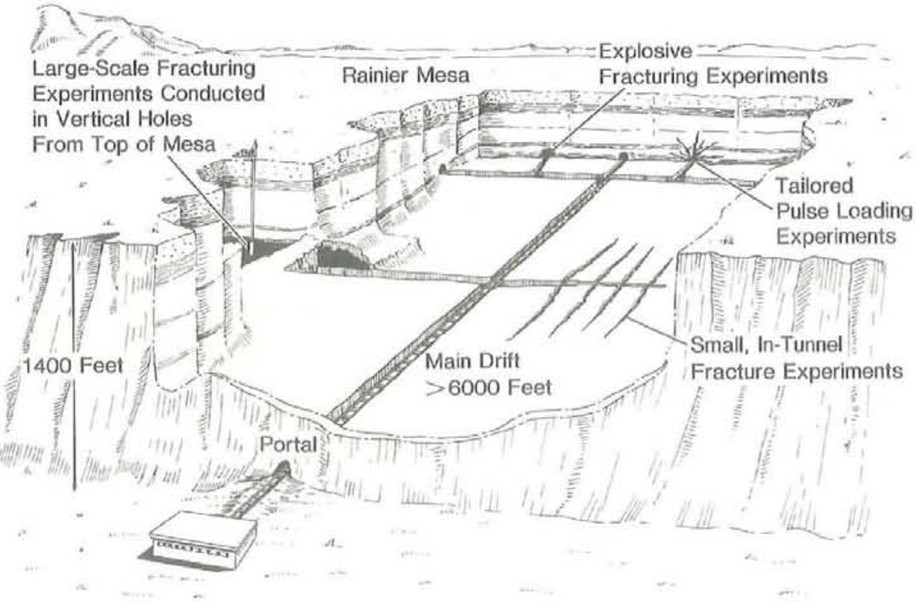
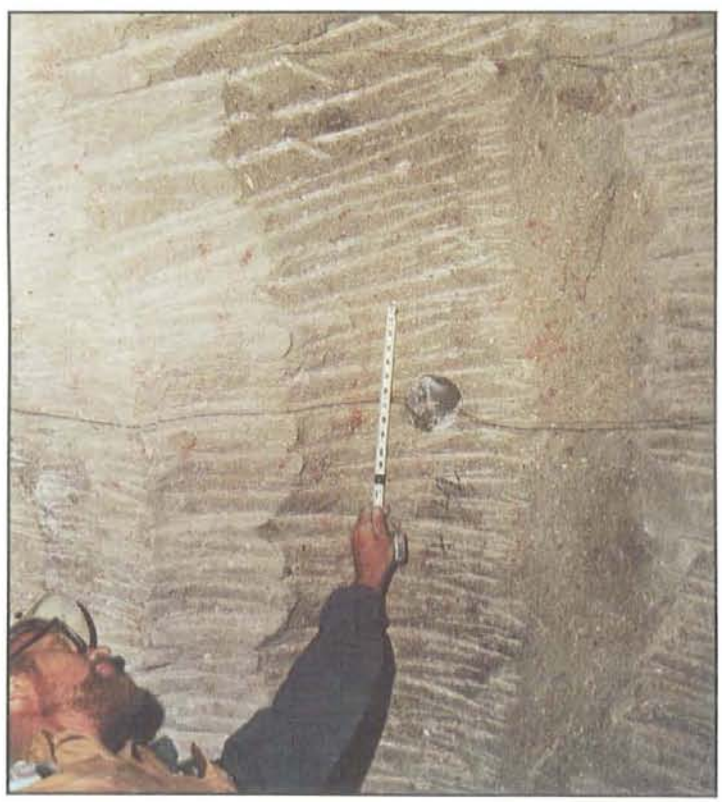


Figure 12
In a tunnel at the Nevada Test Site, we are studying how fractures form and grow in deeply buried rock formations. Fracturing is an important process in extracting gas and other fossil-energy resources.

Figure 13
A borehole and a hydraulic fracture extending from it are shown after they have been exposed in a mineback operation. The fractures visible in the photograph can be characterized and used to upgrade predictive models.



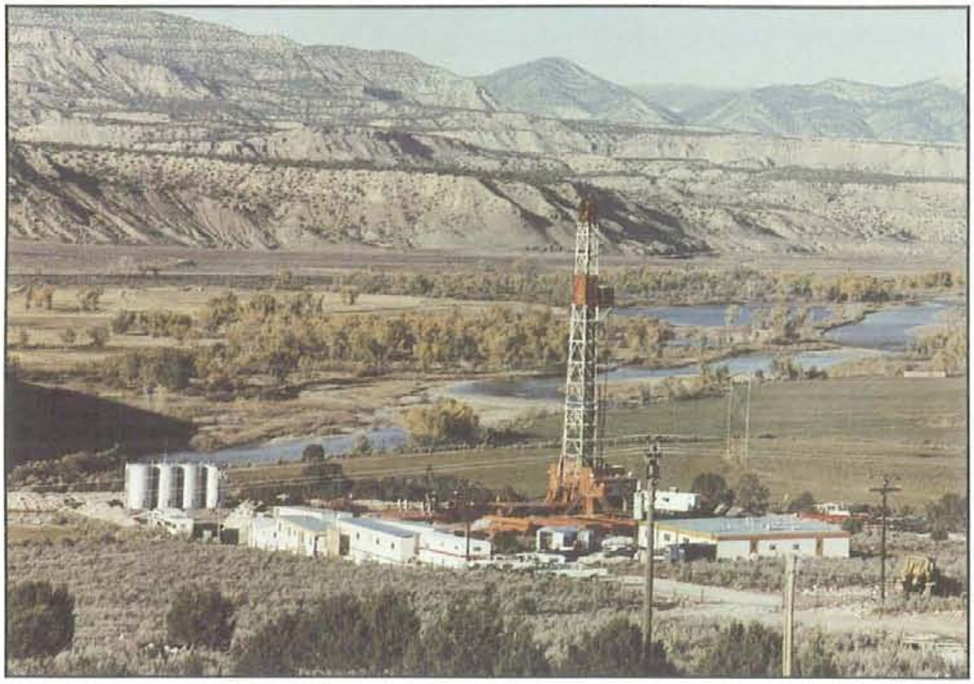


Figure 14
Our field-scale laboratory near Grand Junction, Colorado, is used to study gas extraction from low-permeability discontinuous sands in the Mesaverde geologic formation.

Studies in the Nevada Test Site tunnel also helped us develop a new fracturing technology that overcomes some limitations of both hydraulic and explosive fracturing. In this concept (we call it high-energy gas fracturing), by carefully tailoring the pressurization rate, we create multiple fracture planes radiating from a wellbore. This fracture pattern can be more effective since one or more of the fractures is likely to intercept natural fractures in some reservoirs and thus provide multiple conductive paths to the wellbore. We then developed an overall fracturing system and successfully stimulated gas wells in Devonian shales in Kentucky and Ohio. Now, such multiple fracturing (tailored-pulse) services are offered in the industry.

We have created a field-scale laboratory — Multiwell Experiment (MWX) — to study low-permeability, lenticular (discontinuous) gas sands in the 1300-m-thick Mesaverde formation in western Colorado (Figure 14). This formation is typical of many in the western US that together are believed to contain over 200 tcf ($6 \times 10^{12} m^3$) of gas, or over 10 years' supply at current rates of consumption. The purposes of MWX are to obtain a comprehensive geologic characterization of these gas reservoirs and to develop new technology to produce gas from them. Three closely spaced wells (30-76 m apart) were drilled to 2300-2550 m, penetrating over 30 sand bodies. Core samples were taken to obtain insight into the reservoir and to provide correlation of sands from well to well. We conduct fracturing experiments in one well and observe effects in the sands by means of instruments in the two offset wells. Extensive pre- and post-stimulation well testing provides further information on the character of these reservoirs.

Finally, we have developed a technique to determine the directions (and perhaps with more study, the magnitudes) of in situ stresses in a deep well. When a core is cut and withdrawn from the formation, it deforms slowly as it "relaxes" from the stresses it was under at depth. Measurement of these small distortions in an oriented core is the basis for this anelastic strain recovery (core relaxation) technique. Use of the technique at MWX allowed us to correctly predict the direction of a hydraulic fracture, an important parameter in developing a gas field. We are extending the use of this new analytical method to other oil and gas fields in a joint DOE/industry program.

Figure 15
Our centrifuge facility, one of the world's largest, enables us to subject scale models of oil-shale formations, coal mines, and other types of excavations to forces up to 150 times gravity on accelerated time scales. On it we study how surrounding formations are affected by the creation of underground cavities.

Geotechnical Simulation Studies

An important part of our work is assessing and predicting possible ground motion (subsidence, compaction) associated with the extraction or in situ processing of fossil fuels. To understand these phenomena, we build scale models of geologic formations and subject them to increased gravity loading on a centrifuge. This technique permits us to dramatically accelerate time with a gravitational field and to record, with high-speed photography and other instrumentation, event sequences that may lead to surface ground motion. These simulations provide data to verify computer models with which we can predict behavior of field projects.

Using actual materials, we can build scale models of oil-shale formations, coal mines, fluid-filled reservoirs, and other subterranean structures. With the centrifuge we can subject the models to forces of up to 150 times gravity (Figure 15). Relying on mathematical relationships that define both temporal and dimensional scaling factors, we determine whether the roof above a created cavity will collapse, whether the collapse can lead to surface motion, and the time frame in which these events may occur. Our centrifuge, among the largest in the world, has been tremendously important in helping us understand and verify problems related to subsidence of underground cavities.

Using this technique, we modeled and tested on the centrifuge an underground coal-gasification project near Tono, Washington. We then modeled the created underground cavern using computer codes named RUBBLE and BLOCKS. The field experiment entailed burning the coal underground rather than bringing it to the surface. But since the coal deposit supports the layers of rock above, removing it, whether by in situ gasification or extraction, causes some of the overburden to collapse. Our model predicted the surface effects of creating different cavity sizes by removing different amounts of coal. Results from actual post-burn drilling operations correlated closely with our modeling results. Extension of this powerful technique to the extraction of other types of fossil fuels is a continuing project.

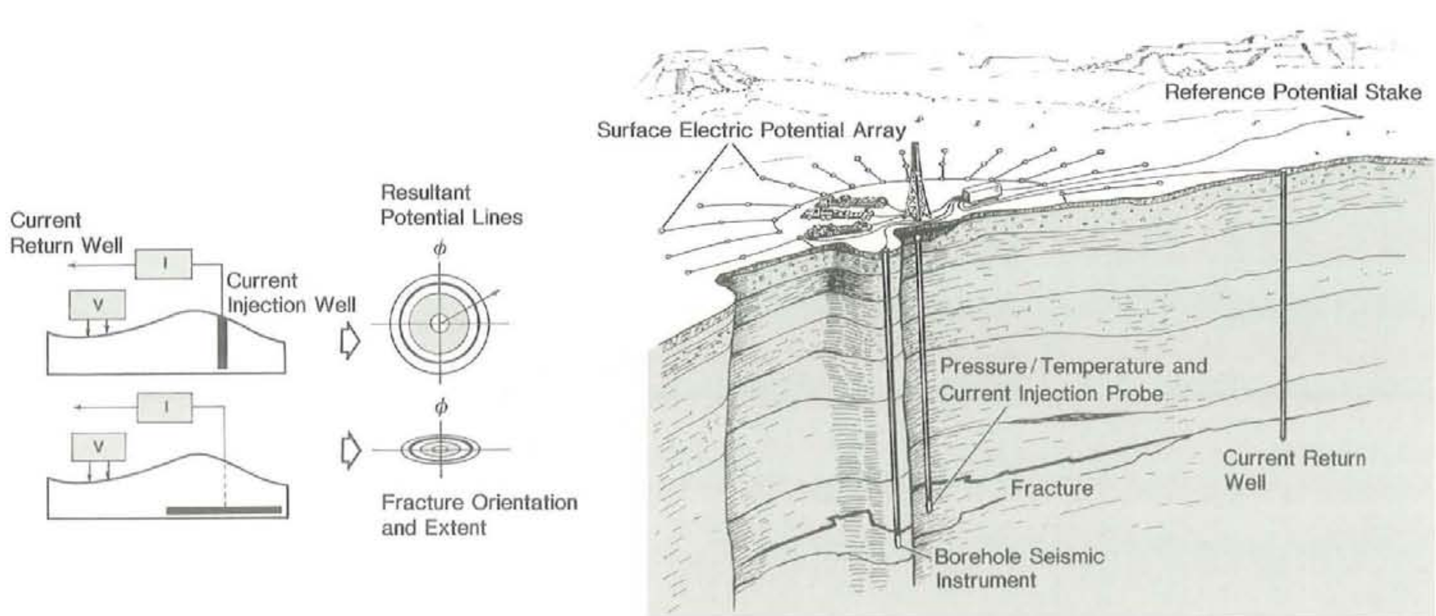


Figure 16
Among the diagnostic methods we have developed to measure underground processes is the surface electrical potential (SEP) technique. Current is injected into the ground and the resulting distribution of electrical potential is measured on the surface. SEP can measure subsurface characteristics nonintrusively since no instrumentation has to be lowered downhole and the process does not interfere with other operations.

Diagnostics/Instrumentation

A major need in fossil-energy production today, particularly regarding enhanced recovery, is to measure how an underground process is proceeding and to determine what controls are needed to improve extraction. To understand what is occurring under the ground, we have developed a number of diagnostic methods, with emphasis on three techniques: surface electrical potential (SEP) measurement, microseismic diagnostics, and controlled-source audio magnetotelluric (CSAMT) measurements.

The first, SEP distribution, relies on electrical resistivity differences between a process zone of interest and its host formation. The technique works by injecting current into the ground through the process-stimulation well and then measuring electrical potential on the earth's surface (Figure 16). If the underground formations were homogeneous, potential lines would register as circular and concentric. When discontinuities are present, whether natural or artificial, lines of equal potential are distorted. For example, by injecting a highly conductive fluid into a fracture we have created, the SEP technique can be used to establish the direction of the fracture. No instrumentation has to be lowered downhole, and there is no interference with other operations in the area.

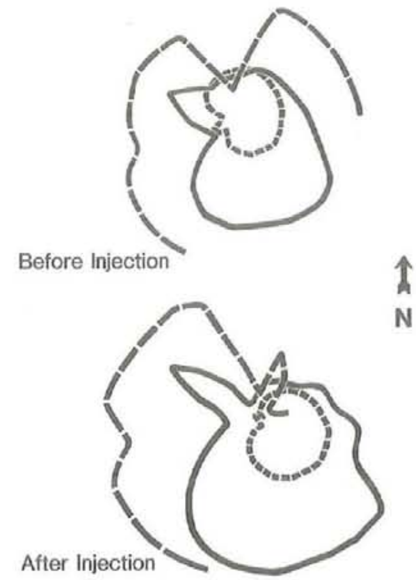
The SEP system was fielded during chemical treatment of a geothermal reservoir in the Beowawe Field in north-central Nevada. Objectives of this SEP test were to determine the sensitivity of the technique to such chemical treatments and to map the direction of the treated zone. Analysis of the test data indicated that the SEP system is extremely sensitive to chemical treatments and that it provides a substantial amount of information regarding directionality of the treatment (Figure 17).

To make in situ microseismic measurements, we lower a listening device with three mutually orthogonal geophones (Figure 18) down a wellbore and lock it against the side wall. If rock fracturing is occurring, we can detect a component of the energy release. If enough is known about the geologic medium's properties, the direction whence the sound emanates and the distance to that point can be determined from velocity hodograms (graphs displaying the polarization of seismic signals). A statistical map of the process zone unfolds as stimulation continues.

Preliminary testing of this method in our Multiwell Experiment in Colorado has been successful. We place seismic tools in two of the wells and create a hydraulic fracture from a third by perforating the casing at the selected depth and injecting fluid into the formation. Seismic tools at near the same depth pick up acoustic emissions as the fracture grows, and the direction

Figure 18
The state-of-the-art borehole seismic tool designed and fabricated by Sandia may play an important role in monitoring energy extraction processes ranging from thermal to hydraulic stimulation of oil and gas wells.

Figure 17
Changes in the surface distribution of equipotential lines surrounding a well used for injecting acids into a geothermal reservoir can be used to gain information about the geometry of the stimulation zone.



and height of the fracture can be inferred (Figure 19).

Another diagnostic technique is CSAMT. Like SEP, this is a surface process that requires no subsurface equipment and depends on electrical properties of the geologic formation for its information. A long, grounded, surface dipole antenna is placed over and near the formation of interest. Waves generated by this antenna at prescribed frequencies travel into the formation. As they encounter layers or areas of the formation that have significantly different electrical properties (i.e., inductance, resistivity), they are scattered and/or reflected. A detector connected to a mobile short surface antenna records magnetic- and electric-field information that is used with analytical models to infer the geometry of the subsurface region of interest. We have used this technique to monitor coal-mine fires, in situ combustion processes, steam flooding for EOR, and underground coal gasification in the field. We also have performed laboratory tests to measure reservoir electrical-property changes for these processes. While the technique is still developmental, lab tests show large electrical-property changes. Field measurements have successfully shown the extent of an underground process and, when performed at sequential time intervals, have detected changes.

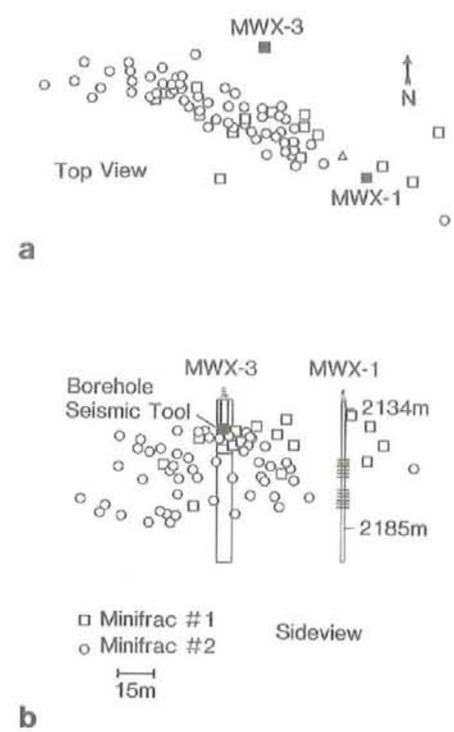


Figure 19
Acoustic emissions resulting from rock fracture during hydraulic stimulation of gas-bearing sand are recorded by our seismic tool and used to infer both the direction (a) and the height (b) of the fracture. Each data point represents the source of an acoustic emission.

BOX B

Offshore Technology

Current projections are that any new large oil or gas fields found in this country will be in offshore regions. DOE, with the Minerals Management Service of the Dept. of the Interior, has established a program to characterize these regions in terms of seismic activity, unstable seafloor sediments, large ice movements, and ice properties. As our contribution to this program we have developed the Seafloor Earthquake Measurement System (SEMS) to measure sediment response to seismic activity. The unit contains a three-axis accelerometer, a solid-state bubble memory, batteries for up to three years of unattended operation, and an acoustic telemetry system for data retrieval.

Four SEMS units were placed in the Santa Barbara channel in 1980, and near the end of its lifetime, one of the units recorded a seismic event centered on the California coastline nearby. We are comparing the SEMS data with those from a nearby land-based unit as part of a long-term effort to determine how seabed sediments alter transmission of seismic energy as compared to transmission through earth. The 1980 data were provided to the oil companies that sponsored deployment of the units.

Recently an improved SEMS design was deployed in the Beta field off Long Beach, California. It is located near an offshore platform of the Shell Oil Company, which sponsored the unit's fabrication and deployment. For two seismic events in July 1986, the SEMS unit recorded seabed response to provide a data base for Shell to use in platform-response models. The unit is monitored periodically by means of a mobile data-acquisition system in a small boat. Operation of this SEMS unit is allowing us to proof-test the design for possible later use in more seismically active regions near the Aleutians.

Strategic Petroleum Reserve

In 1975 Congress authorized establishment of the Strategic Petroleum Reserve (SPR) to mitigate the effects on our economy and national security of another oil embargo like that of 1973. The plan calls for the storage of 750 million barrels (bbls) of crude oil in leached or mined caverns in Gulf Coast salt domes. By the end of 1985, nearly 500 million bbls had been stored in 36 leached caverns and one mine in south Louisiana and southeast Texas. Since present US consumption is about 15 million bbls a day, the total storage goal represents about a 50-day supply. However, in terms of imported oil, SPR at capacity will represent a five-month supply at 1985 import rates, and in terms of oil imported from OPEC-aligned middle-east countries, represents almost a one-year supply.

We provide engineering support to the New Orleans DOE/SPR project office on a variety of geotechnical issues. Typical are site-characterization studies, cavern spacing within a salt dome (Figure 20), cavern and well testing, salt-leaching studies for cavern development, instrumentation and tool development, long-term cavern creep studies, and analyses of wide-ranging site-specific geotechnical problems. These programs first help establish the suitability of a salt cavern for oil storage and then provide ways of assessing and monitoring cavern integrity and its long-term behavior while filled with oil.

One way to create a salt cavern is to pump hundreds of millions of barrels of water into the salt dome to remove the salt. Our leaching research has revealed how cavern shapes develop (Figure 21). Associated analyses determine where high stress concentrations may occur and assess subsequent creep (cavern closure) caused by removal of salt. Excessive stress may cause large pieces of wall or roof to break off. We are also developing acoustic (sonar) and electromagnetic (radar)

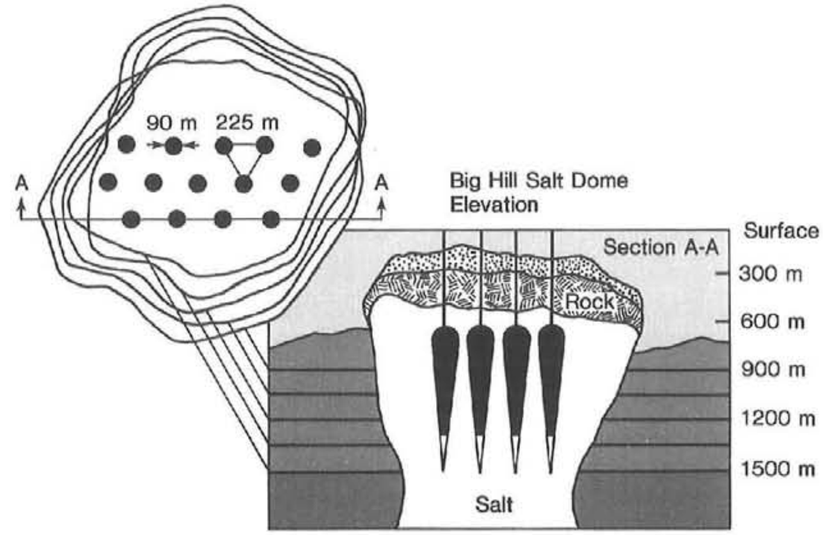
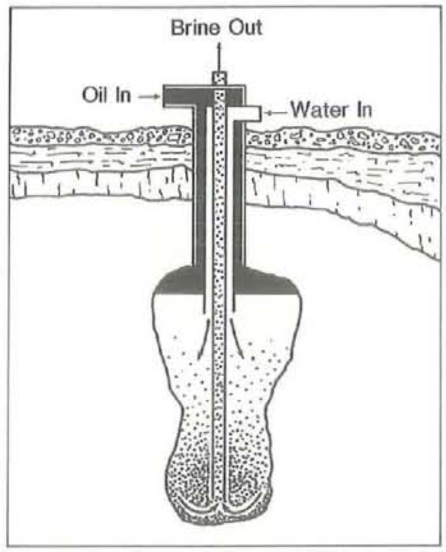


Figure 20

An important part of our early SPR work was the study of cavern shape and spacing within a salt dome. These analyses were based upon specific dome geology and salt structural stability; they helped define optimal layout of caverns in the dome.

Figure 21
Our leaching codes predict how caverns are shaped as water is selectively injected at different depths along an entry well in a salt dome. After the top is formed, crude oil is continuously added at the cavern top as lower parts of the cavern are leached to their final shape in a "leach-fill" mode.

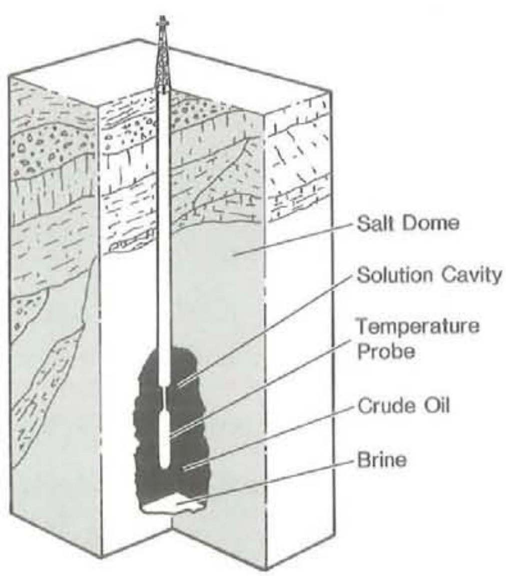


instrumentation to measure the volume and shape of oil-filled caverns (Figure 22) and the integrity of cavern entry wells.

In general, as the reserve is filled, emphasis has shifted from site evaluation and leaching studies to assessing long-term cavern integrity and developing diagnostic instrumentation to ensure safe oil storage.

For additional information, call Bill Marshall (505) 844-2964

Figure 22
As more and more caverns were formed and filled with crude oil, we turned our attention to the question of assessing long-term, safe storage of the oil. New instrumentation is being developed to operate in large-diameter casings and large oil-filled caverns. Conceptual application of a high-resolution temperature-logging probe is shown.



Magma

Figure 1
The 1979 eruption of Kilauea Iki in Hawaii produced low viscosity basaltic magma typical of volcanoes in Hawaii. These magmas release energy much less abruptly than do the explosive and volatile high-silica melts of Mount St. Helens.

Magma bodies at temperatures from 800° to 1200°C exist within the earth's crust at drillable depths. In our magma energy program we are investigating the feasibility of tapping these reservoirs to obtain high-quality energy (Figure 1).

In the first phase of the program (I976 to I983) we examined the scientific feasibility of extracting energy from magma. The idea was deemed feasible after we had addressed the following issues:

1. *Can we locate and define magma bodies using surface physics and geology?* Yes, seismic survey results can be combined with other data to define magma systems.

2. *If we find a body, can we drill into it?* Extensive rock-mechanics research at Texas A&M showed that volcanic rocks undergo brittle failure up to melt temperatures, and boreholes filled with fluid remain stable. This means standard drilling techniques can be used in magmatic formations and boreholes will remain open. We also have drilled through molten slush at 1070°C in the Kilauea Iki Lava Lake, Hawaii, and Icelanders have penetrated molten rock in their geothermal work.

3. *Will drilling and extraction materials survive in molten rock?* Using gases and solids erupted from volcanoes, we determined compositions of magma bodies at depth and simulated them in the laboratory. These simulated magmas were then used to study material compatibilities. A number of materials, including superalloys, satisfactorily survived 1000-hour tests at temperatures to 1200°C.

4. *Can energy be extracted from the melt?* Heat-transport properties of molten rocks were defined through research, and heat-extraction experiments were carried out in the lab as well as in Kilauea Iki. Both theory and experiment verified that energy can be extracted using any of several heat-transfer processes.

Magma Locations

Active and currently passive volcanoes in the western US are visual evidence of magma systems near the earth's surface. The USGS has estimated that significant magma bodies exist within 10 km of the surface (USGS Circular 790 includes estimates of over 50,000 quads [1 quad equals 10^{15} BTU or approximately 10^{18}J] of energy available in molten rock in the US; current total US usage is 75 quads per year). Since industry has drilled to 10-I2 km, these bodies are at accessible depths. However, no one has actually drilled into a magma body. Therefore, we cannot certify that magma exists where predicted, or despite our positive results in lab experiments, that hardware currently available can survive those environments.

Another exciting geothermal region is along ocean ridges where "smokers" have been found. An Ocean Drilling Program submersible off the State of Washington has put a temperature probe in the top of a smoker and measured 410°C at a water depth between 2700 and 3000 m. There the crust is thin and the magma is at the edge of the crust. This magma is basaltic, is very fluid, and has good heat-transfer properties.

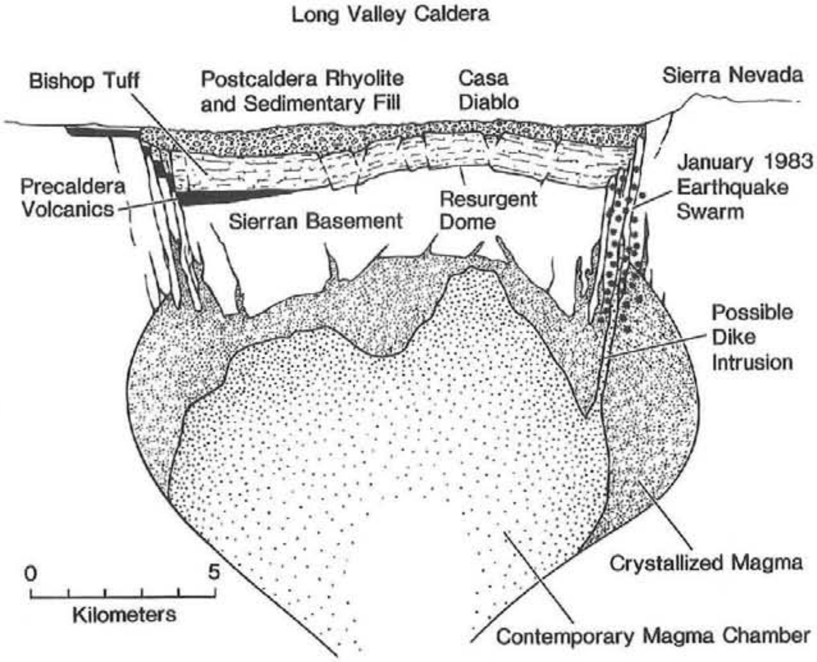


Figure 2
This semiquantitative model of a magma chamber under the Long Valley caldera in California was constructed from extensive seismic studies combined with results from USGS research. Santa Fe Industries has donated a well site and facilities near Casa Diablo where we plan to drill into the well-defined magma chamber 4-6 km below the surface.

Magma Types

We usually think of lava in terms of volcanoes that spout huge plumes of molten magma. Those are primarily low-viscosity basalts (Figure 1). But on the continent, around Mount St. Helens for example, magma compositions are more andesitic or rhyolitic, which are silica-rich. As silica content increases, magma becomes more viscous and likely contains more water. The viscosity of high-silica melts can retard the escape of expanding magmatic gases, resulting in violent explosions like the one at Mount St. Helens. We are now primarily looking at extracting energy from areas of the continent where the magmas are undoubtedly rhyolitic and andesitic.

Research Issues

What scientific and engineering problems need to be solved before energy can be extracted from deep-lying magma bodies?

First, we must be able to identify magma locations well enough to mount a drilling program. Extensive seismic and other geophysical surveys have identified the Long Valley caldera and Coso Hot Springs, California, as places where magma bodies lie 4 to 6 km deep (Figure 2). Industry is providing a drill site and pad so we can initiate drilling in Long Valley.

Second, we need to understand the chemistry and properties of these andesites and rhyolites with their dissolved gases at in situ temperatures and pressures. Geochemical results from studies of erupting solids, liquids, and gases are being used to thermodynamically reconstitute in situ properties.

Third, we are addressing the engineering challenges of drilling into 900°C molten rock and developing an energy-extraction process. Past successes in tapping molten magma in Kilauea Iki suggest that it can be done, but the engineering challenges are extensive.

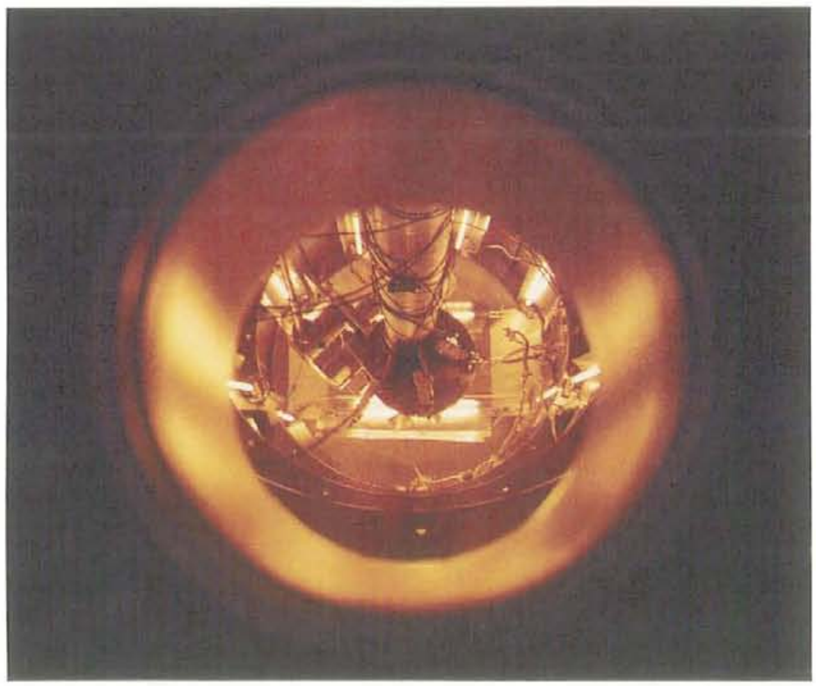
For more information call Jim Dunn (505) 844-4715.

Magnetic Fusion Technology

Energy release from the fusion of deuterium and tritium nuclei continues to promise an environmentally attractive energy source. Fusion physics is actively studied in many countries on large experimental facilities, notably the tokamak, reverse pinch, and mirror machines.

Several aspects of fusion energy are under study at Sandia. These include the interaction of plasma with material surfaces, research on the behavior of tritium in solids, and the development of special materials. Research emphasis is on questions about materials and processes in high-heat-flux areas of the reactor

- Which materials and engineering designs will survive heat fluxes of 1-100 kW/cm^2 in the presence of high vacuum and strong magnetic fields?
- How can the plasma edge be contained without injecting impurities that would quench the plasma?
- How will plasma impurities, such as helium ash, be removed from long-pulse or continuous reactors?



High-temperature, high-vacuum test chamber used to evaluate moveable limiter support structures. View through a window shows quartz lamps that produce temperatures equal to those on the inside walls of a tokamak (≈350°C).

Our research results are also being tested in joint efforts with physicists in operating systems such as the TFTR at Princeton, TEXTOR and ASDEX in West Germany, TORE SUPRA in France, and JET in England (Table).

Table. Pumped Limiter Designs for Fusion Experiments

Facility	Location	Sandia Activity
JET	Culham, U.K.	Collaboration on material and limiter designs
TFTR	Princeton, N.J.	Collaboration on materials and limiter design.
TEXTOR	KFA Juelich, W. Ger	ALT-I limiter designed, installed, and operated
		ALT-II continous limiter designed; construction and installation a joint W. Ger-Japan-US program
TORE SUPRA	Cadarache, Fr	Limiter being designed and built; definition stage
ASDEX	Garching, W. Ger	Experiments with divertor operation to be followed by pumped-limiter studies

High-Heat-Flux Materials

Materials problems are pervasive in fusion technologies. Certain components such as limiters (devices for removing impurities from the edge of the plasma in a reactor) require that materials survive in contact with the plasma without producing impurities that would poison the fusion reaction.

These materials must have the following characteristics:

- A low atomic number
- Nonmagnetic
- High thermal conductivity
- Fracture resistance
- Stability at high vacuum and temperature
- Low retention of gases, particularly hydrogen
- Radiation resistance.

A recently completed study focused on beryllium. The work was sponsored by the Joint European Torus (JET) program, with beryllium evaluation being a cooperative study between Oak Ridge National Laboratory and Sandia. The thermomechanical response of a beryllium limiter structure subjected to a plasma pulse was modeled using a two-dimensional elastic/plastic stress code (Figure 1). Microfracturing was predicted, and experimental testing was required to evaluate severity of the cracking. The Sandia Electron Beam Test Facility was used to apply 300-ms heat pulses at 2.5 kW/cm^2 to test specimens. As predicted, microcracking occurred after 100 thermal pulses and grew during the next 1000 cycles, but then stopped, and there was no material failure during an additional 8900 cycles.

These analytical and laboratory studies (Figure 2) were followed with testing by Oak Ridge scientists in their ISX tokamak facility. During these studies the beryllium samples were overtested to melt (Figure 3). Despite melting and microcracking, the samples retained their integrity and verified model predictions (Figure 4). These results have given

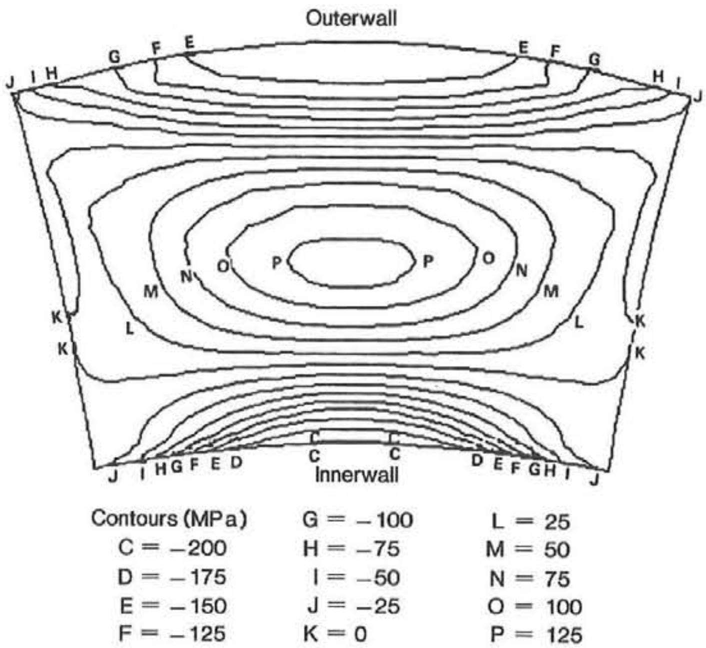


Figure 1
Calculated elastic-plastic stress response of a beryllium limiter subjected to a plasma pulse. Contours at 15 s into the experiment are plotted on top of the deformed shape of the limiter. Contour lines are 25 MPa apart.

us confidence in beryllium limiter plates and such designs are now being considered for use in the JET tokamak.

Impurity-Control Systems

Results of research on high-heat-flux materials and plasma/material interactions led to the design of components that interact directly with the plasmas. Current options to define plasma limits and remove plasma impurities include divertors* and pumped limiters. Our work emphasizes the design and testing of pumped-limiter systems (Table), that define the plasma edge and pump impurities from it.

The ALT-I limiter (Figure 5) was designed and built at Sandia for joint German-UCLA-Sandia experiments in the TEXTOR experiment at Juelich, West Germany. Limiter operation was successful in TEXTOR, with demonstrated removal of the plasma edge and control of plasma particle density.

The ALT-II limiter has been designed and is being built in a joint German-Japanese-American program. It will be a continuous-belt limiter that encircles the torus with eight pumping ports. Challenges include: (1) developing complex, nonmagnetic drive systems for adjusting the limiter blades inside the reactor; (2) designing the complex

*A divertor magnetically guides the plasma edge into a chamber, where impact with a wall removes the ions and impurities that have diffused into the outer "scrape-off" layer of the plasma. Impurities can then be pumped from the chamber. A pumped limiter accomplishes the same goal by moving a mechanical duct into the plasma edge to extract impurity particles and pump them from the reactor.

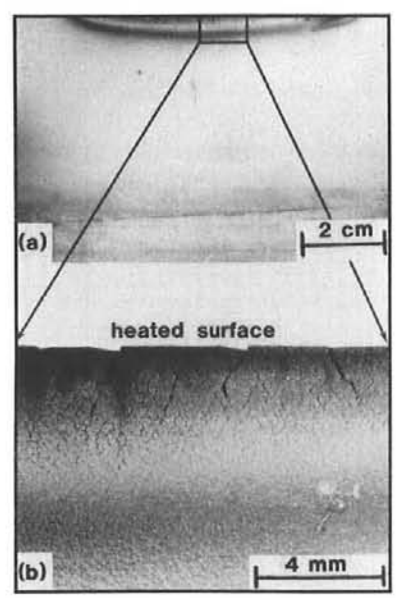
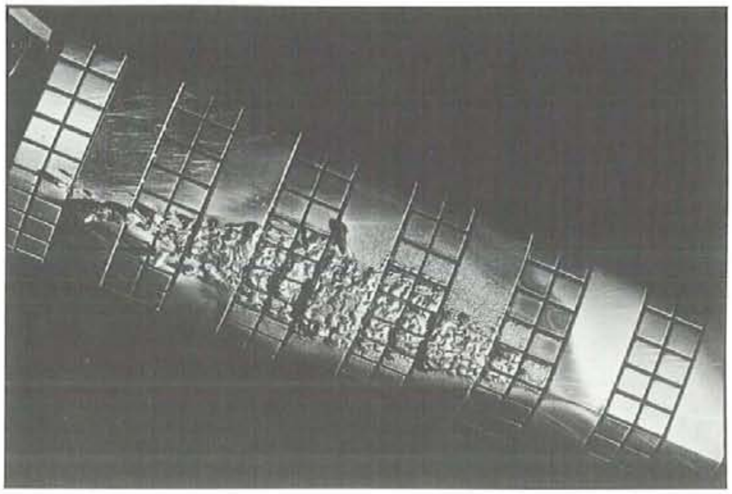
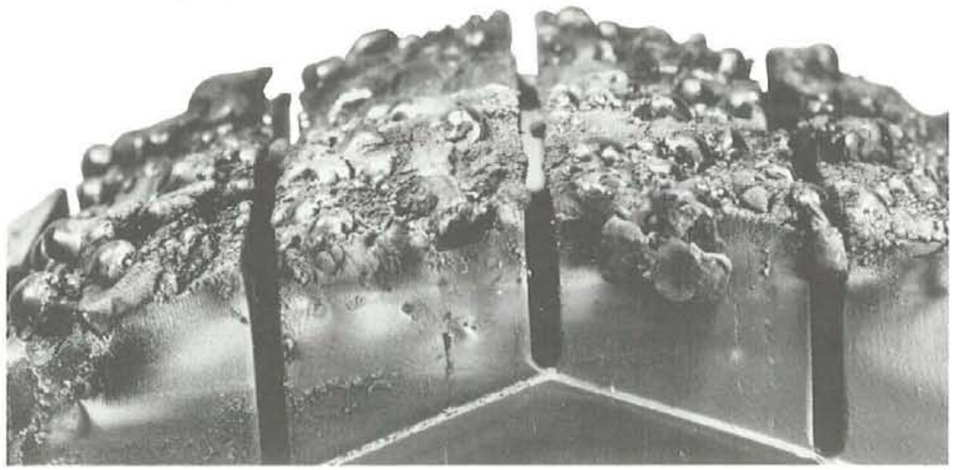


Figure 2
Photomicrographs of beryllium tile after exposure to 10,000 thermal fatigue cycles in Sandia's electron-beam facility. Microcracks extend to a depth of 4 mm.



ORNL Photo

Figure 3
A beryllium limiter was exposed in the ORNL experiment until it began to melt, but it retained structural integrity.



ORNL Photo

Figure 4
A photomicrograph of a similar sample after exposure to 0.3-s pulses of 2.5 to 5.0 kW/cm² for 5000 cycles at ORNL. Melting occurred when the design load was intentionally exceeded. Slotting of the sample reduced fatigue cracking, as predicted by stress analysis.

Figure 5
View of ALT-I module showing instrumentation probes in the throat region.

blade curvature to match the plasma field lines; (3) selecting materials for high-heat-flux surfaces; and (4) designing structures to withstand stress fluctuations and plasma disruptions. The current design uses graphite tiles for the high-heat-flux surface. The graphite is undergoing extensive high-heat-flux testing in our e-beam facility.

Plans are being initiated to participate in evaluating the diverter on ASDEX, a fusion research facility at Garching, West Germany. The goal will be to design a pumped limiter for use in the same facility to compare the two impurity-control schemes. Active programs concerning impurity-control components are also under way for the TRTF, TORE SUPRA, and JET.

For more information, call Wil Gauster (505) 846-I648.

Geothermal Energy Sources

Geothermal resources already contribute 1300 MW of power to electric grids in the western US. However, obtaining access to a potential additional 200,000 MW, as well as much more in magma and hot dry rock resources, depends on advances in technology.

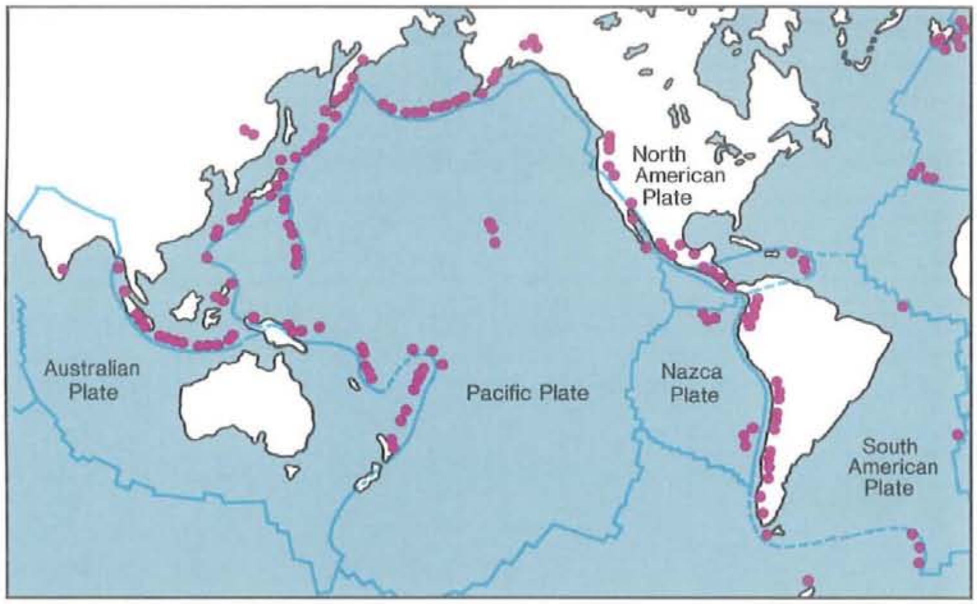


Figure 1
Volcanoes are active along the midocean ridges, including the "Ring of Fire," which abuts the coasts of North and South America and circles through the Aleutians and Japan. Volcanic activity in the western US (e.g., Mount St. Helens) arises from the friction of the Pacific tectonic plate sliding under the North American plate.

Heat escaping from inside our planet is most evident in volcanic eruptions seen in the "Ring of Fire" (Figure 1) that encircles the Pacific Ocean, including recent eruptions in Colombia, Mexico, and the US. Circulating groundwater may absorb magmatic heat and reappear as steam in areas like the Geysers, California, and Yellowstone Park, Wyoming. Water interacting with hot rock may also appear as hot springs or warm-water resources and is used in many areas for heating or for treatment of human ills. A goal of the geothermal industry is to effectively use these resources to provide heat and power to meet energy needs.

The Geysers, north of San Francisco, produces about 1.3 gigawatts of electricity from geothermal sources and an additional 5 to 10 gigawatts is predicted within 10 years. Another 10-20 gigawatts is expected to be produced in the Imperial Valley and elsewhere in southern California.

Tapping geothermal resources is not as simple as bringing in an oilfield drill-rig, punching down a hole, and producing steam or hot water. In fact, little regular oilfield experience is directly convertible to geothermal use. The most significant differences between oil or gas drilling and geothermal work are that the geothermal environment is hotter, is in harder rock, and is more corrosive. A nominal geothermal reservoir will run to 200° or 300°C. Even when gas wells have gone to 10 km, like the Bertha Rogers well in Oklahoma, and hit molten sulfur, the sulfur is still at or below 200°C.

Geothermal fields are almost always in volcanic areas, so the rock that has to be drilled is basalt, andesite, or tuff; oil and gas wells are drilled through softer sandstones and limestones. Because the rock we have to penetrate is very brittle, it is highly fractured, again in contrast to oil and gas formations.

Most oil and gas wells are overpressured, whereas underpressure is a major geothermal problem. This means that the pressure in a producing geothermal zone is less than the hydrostatic pressure on the drilling fluid. When that happens, fluids put down the hole disappear into the formation. This phenomenon, called lost circulation, is one of the major costs in drilling geothermal wells.

Another consideration is that in extracting geothermal energy, whether for electricity or heat, half of the original investment and operating cost is in the well; the other half is in surface equipment. Costs of developing a geothermal well are 2 to 5 times those of an oil or gas well at equivalent depths (Figure 2). An average geothermal well is 2 to 2.5 km deep and costs 1 to 2 million dollars. This well cost has a tremendous impact on the overall cost of developing geothermal resources.

About 80 geothermal wells are drilled annually in the US, compared to about 60,000 oil and gas wells. Partly because of the modest size of the geothermal effort, service industries that provide drill rigs, strings, and bits to the drilling industry have low interest in developing technologies for geothermal. Drilling research is being done currently in Japan, Norway, France, and the Netherlands, but little is sponsored in the US.

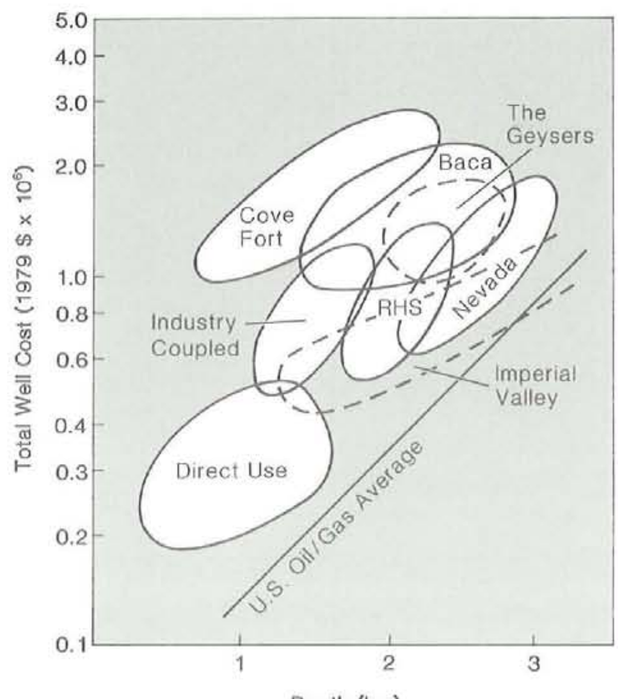


Figure 2

Geothermal well costs for each of the geothermal areas are compared to those of average US oil and gas wells. Geothermal drilling expenses are significantly higher because of hard rock, corrosive fluids, fractured formations, and lost circulation.

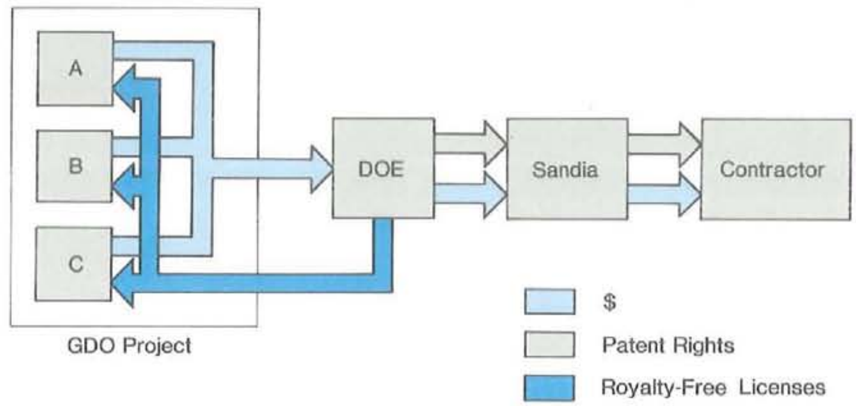
Sandia's Geothermal Program

About 15 years ago, when DOE established a nationwide geothermal program, Sandia was asked to determine whether there were existing or incipient technologies that could reduce the time and costs of drilling and well completion. The assignment covers drilling a hole, putting in casing, fracturing the formation, and supporting technologies needed to gain production. In short, could we do anything to directly impact the cost and economic viability of geothermal drilling?

To answer that question, we have a technology development program oriented toward drilling, logging, and wellbore matters. An industry-based technology review panel meets with us twice a year to critique our research results and plans. Overall, DOE guidance, combined with the industry critiques and peer review of technical publications, has resulted in a program that has generated extensive technology transfer.

BOX A

Geothermal Drilling Organization (GDO)



Geothermal drilling technology is similar to that used to drill oil and gas wells. Because the geothermal market is about 0.1% of the combined geothermal, oil, and gas market, there is little economic incentive for industry to develop specialized technology (bits, drilling fluids, instrumentation, etc.) to meet the needs of geothermal operators. To address this problem, the DOE, through Sandia, offered to share on an equal basis with industry the expense of developing technology to meet the needs of the geothermal drilling industry.

The GDO has been formed to provide industry representation in this partnership. As noted in the flow diagram, special provisions for handling the patent rights of all parties have been developed. The GDO comprises 22 members from industry who establish the priorities of projects to be funded. Sandia acts as the DOE representative to provide 50% of the funding and the contract-management function.

The first project selected by the GDO is development of a high-temperature acoustic borehole televiewer (p. 33). A company has been chosen by industry to develop, build, and test one. We have proved that it is feasible, and have given everyone the drawings and specifications. The company will then guarantee service to the industry for four years, and industry will guarantee $400,000 a year or so to the company for the service. We will be working directly with the company. After they have tested a product and shown it to industry, we will retain only a consultant role.

Borehole Mechanics

In a geothermal well there is a casing to protect the aquifers and keep the borehole walls from caving in. The casing is a steel tube lining the 600 to 3000-m hole. After it has been installed, cement is pumped down the casing to the bottom, where it squeezes out around the sides of the casing back up to the surface. When this cement sets, it must form a permanent and evenly distributed bond between the casing and the formation. The bond keeps the casing from expanding during thermal cycling and also keeps geothermal fluids from leaking up outside the casing.

Many problems occur in completing these wells (Figure 3). In some cases the bond is not complete and uniform from the bottom of the casing to the top. The formation, cold after drilling is finished, is reheated when the well produces steam. The casing then expands and can buckle at its unsupported points, risking a blowout (an uncontrolled release of steam), which is hazardous to personnel and can ruin the well.

We did a large number of calculations on casing stresses, identified commercial codes that are available for analyzing problems, and developed a set of analyses that are now used in industry for evaluating casing stability.

In addition to casing studies, we are developing technologies to characterize and plug lost-circulation zones. These are highly fractured regions that gobble drilling fluids and tend to collapse, trapping the drill string. None of the materials used by the oil or gas industry to plug these lost-circulation zones are adequate in geothermal environments. Cellulosic products like paper or cloth disintegrate in the hot brines. The list of lost-circulation materials used currently in the geothermal industry runs to several pages. Mattresses, cotton-seed hulls, wood chips, and other items have been tried. In the Philippines and in Indonesia, some places with lost-circulation regions are like small-scale Carlsbad Caverns. Whole palm trees, stripped of their branches, are dropped into holes in attempts to plug the loss zones.

We are developing analytical and experimental models so we can evaluate flow through multifractures. A large-scale simulation facility (Figure 4) is gathering lab data on cross-flow phenomena, such as where a fracture encounters a borehole. Analytical results are upgraded by lab data. Models will then be evaluated in the field.

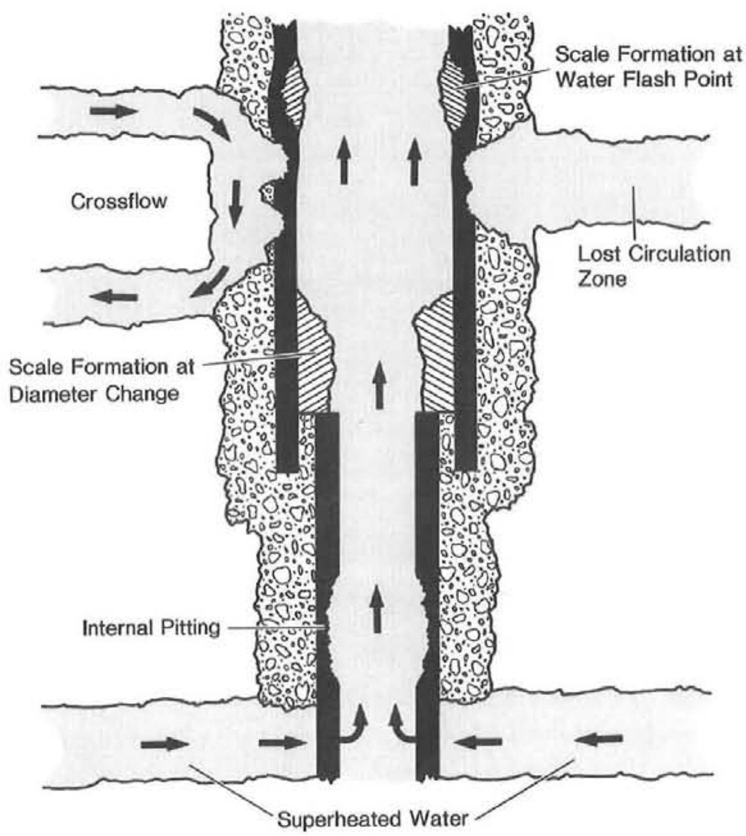


Figure 3
This sketch depicts some of the problems of drilling into a geothermal area. Inadequate wellbore completion can lead to collapse of the casing, shutting off flow; to a blowout, causing safety and economic problems; or to possible contamination of local aquifers.

If a formation is highly fractured, can we put in a rigid heat-resistant foam to fill the cracks? Can foam components be pumped down the hole, where they will mix, flow out into the formation and then set, like the foams used for cushioning and other purposes in weapons? A company named Polyplug was interested in this idea and developed a borehole foaming system. To test it, we filled a cardboard tube 1.8 m. in diameter and 4.6 m long with porous rocks, and injected foam using the Polyplug tool. The components mix as they go through the nozzles. Figure 5 shows several tons of rock stuck together with this foam, which obviously would prevent flow through the formation. The system is now being used commercially.

Figure 4
We designed this lost-circulation test facility to resemble the Halliburton facility in Duncan, Oklahoma. The equipment realistically simulates flow of non-Newtonian drilling muds, cements, and lost-circulation materials from a wellbore through a geologic formation. The facility, unique in having a 200°C operating capability, is used to address geothermal well-completion problems.

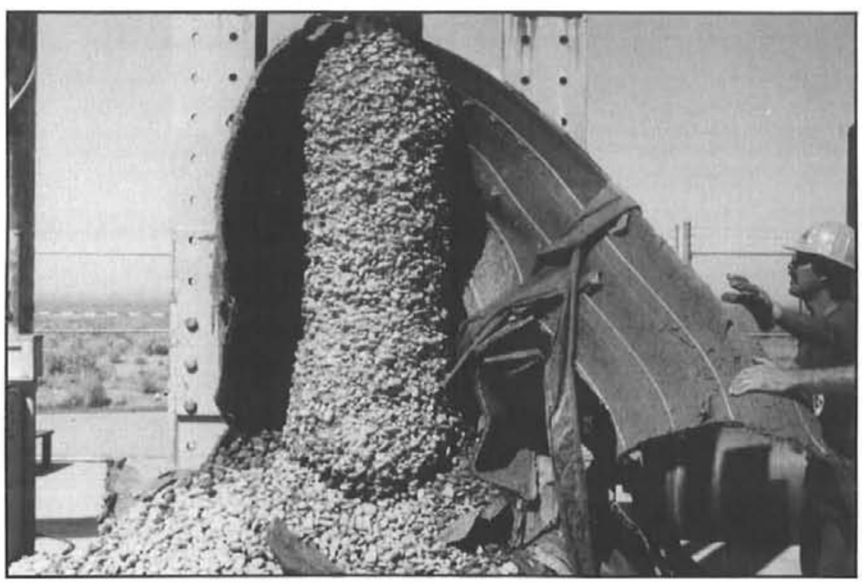


Figure 5
The two liquid components of a urethane foam can be pumped into a well, mixed downhole, and allowed to flow into fractures that are causing lost circulation. This test showed the operating system to be functional.

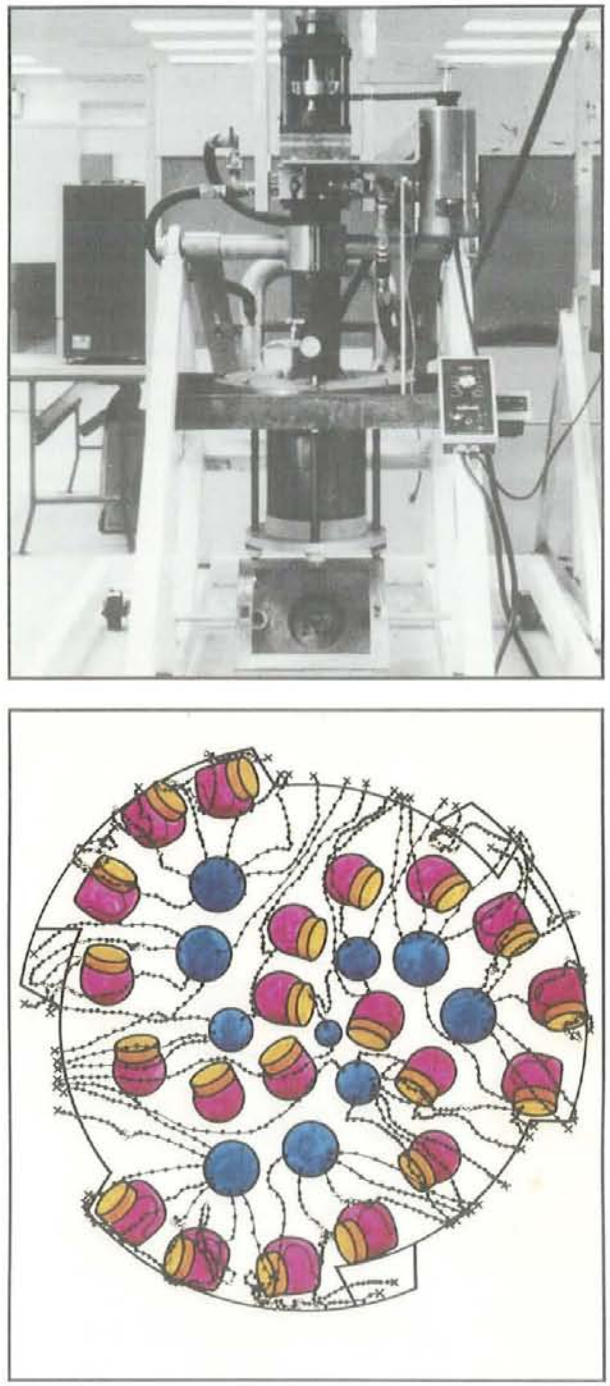
Fluid Technology

This research has to do with muds, foams, and gases pumped through the drill pipe and back up the annulus during drilling to cool the bit, clear cuttings from around the bit, and lift them to the surface.

Flow Around Cutters – Drilling fluid keeps cutters cool and removes debris, serving the same purpose as the cutting oil used during metal machining. The location of drilling-fluid ports in the bit is critical for effective cleaning and cooling. We are examining flow patterns in these bits, and one of our people has developed a simulation facility (Figure 6). With this device we can examine flow patterns and the heat-transfer rate at the cutters. The device has been invaluable for cutter and fluid-port placement. Several manufacturers have duplicated this test facility for their development work.

Muds – We also study drilling muds. Bentonite muds typically used in the industry contain clay in the shape of platelets. In a high-shear zone the platelets line up along the shear fields so that there is a low viscosity, which is needed when the mud goes through the nozzles of a bit. Conversely, when the fluid turns the corner and goes up into the larger-area annulus (a low shear-rate zone), the platelets form a high-viscosity fluid that lifts chips and cuttings out of the hole.

Unfortunately, in a high-temperature regime, bentonite turns into a fibrous material that cannot carry cuttings out of the wellbore. Structural changes in different muds and clays under heat have been examined by researchers at Texas Tech University. Out of this work has come a new set of high-temperature muds based on a clay called sepiolite. Sepiolite is fibrous at room temperature, but when heated it agglomerates into mats that look almost exactly like bentonite. Once



a

b

Figure 6

A drill-bit flow-visualization apparatus (a) lets us examine flow patterns (b) and heat transfer at the cutters as the bit drills through a plastic block. The block is transparent so the flow patterns around each cutter can be seen. This apparatus has been duplicated by four major drill-bit manufacturers to aid in their design efforts.

heated, it forms irreversibly into a high-temperature, stable platelet structure that serves very well (Figure 7).

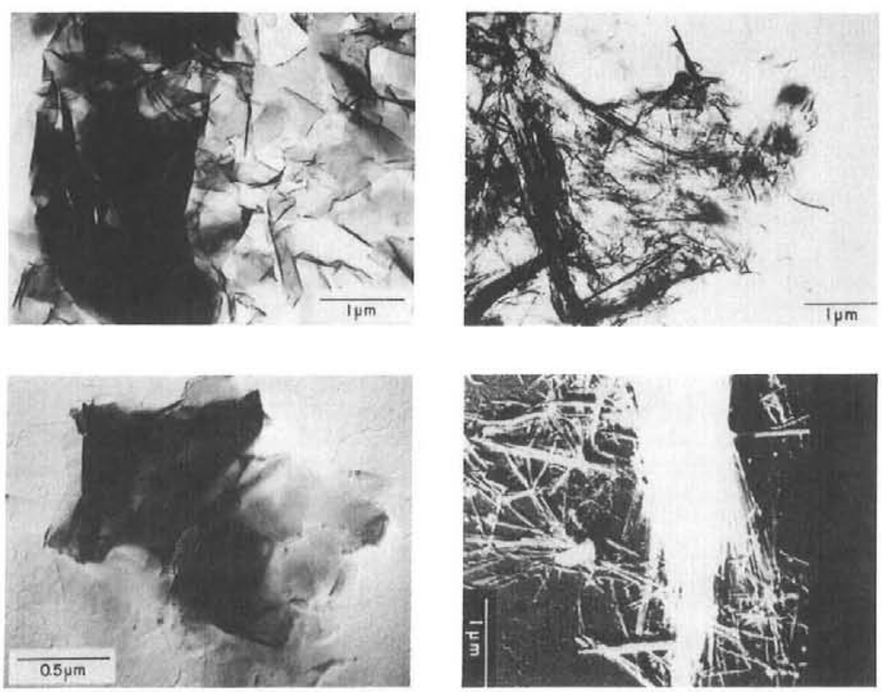
Foams – Many geothermal systems are underpressured, and any muds put down the hole will flow out into the formation. This is not only expensive, but the mud fills needed steam-flow channels in the formation. Worst of all, the mud will not come up the shaft to keep the hole open, and the bore wall may collapse on the drill string, costing hundreds of thousands of dollars for repair.

One way to prevent loss of drilling fluids is to use less-dense fluids. In The Geysers, when drillers get close to a producing zone, they use high velocity air instead of drilling mud cuttings. This causes another problem because air and the underground brines form an extremely corrosive mixture. The stream of air and cuttings is also very erosive, and that too may cause loss of a drill string.

An intermediate solution is to use an aqueous foam (Figure 7). Sandia has worked with foams for many years in weapon and security applications. Our materials group is now experimenting on a foam that will be compatible with brines and remain useful at temperatures of 200° to 300°C. We have evaluated a number of detergent (surfactant) agents in lab and field tests. A series of materials called alpha-sulfonates looks promising.

Foams make good systems because they are light and low in viscosity as they go through the bit. But coming uphole they attain the consistency of shaving cream and lift cuttings quite efficiently. Of course, the foam has to be broken down when it comes out the top, so it can be recycled. We know how to do this in the lab, but we have not proved it can be done economically in the field.

Our materials people are doing research on the mechanics of foam flow. How do we estimate pressure drops? Do the bubbles collapse and re-form? How is heat transferred through the foam? What type of pump is needed? There is a whole area of fluid mechanics and heat transfer involved with foam. Again, industry is interested because they also use foams for tertiary recovery of oil products and in other areas.



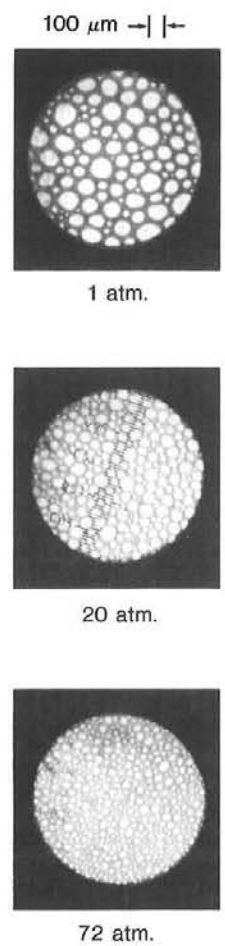


Figure 7
Drilling fluids remove chips from the cutters, keep the cutters cool, and carry chips out of the wellbore. Conventional platelike bentonite muds become fibrous (above) at geothermal temperatures and lose their chip-carrying ability. New sepiolite muds develop a platelike structure at temperature and have been used successfully in geothermal drilling at 400°C. Other research is on foams (right), which are now being studied for use in geothermal drilling.

Rock Penetration Mechanics

Understanding how a drill bit cuts the rock and how the entire drill string behaves is important in effectively designing bits, downhole assemblies, and instrumentation.

Bits – Drill bits in use in the oil/gas industry are typically tricones, in which the cones rotate and crush the rock. The tricone has problems in geothermal fields because the bearings and seals cannot withstand the hot corrosive fluids. An ideal bit for use in geothermal work doesn't have rotating parts, but is a drag-bit design using diamond cutters. This bit actually mills the formation.

In much of our initial work in this area we used synthetic-diamond cutters developed by General Electric. Synthetic-diamond composites about 15 mm in diameter are attached to studs inserted into the bit body (Box B). All drill-bit companies now sell versions of our initial design, and many use the cutter-layout computer program we developed for bit design. We are now studying whether cavitating-fluid jets can interact at the cutter/rock interface to enhance drilling.

Dynamics – What happens during drilling to the drill bit, the stabilizers, and other gear on the string? To use an analogy, imagine a piano wire about 50 feet long attached to a tiny bit. To make the bit at the bottom of the well rotate, the wire must be twisted many times at the top and will become very tightly wound. When workers release an actual drill string at the top, it unwinds many times as they pull it out and release the grips. Further, as the bit chews into the formation, it bounces up and down and slams sideways in the borehole (Figure 8). What effect does this have on the bit and on downhole electronics? Drill-string manufacturers worry about fatigue in the string because they want to sell strings that will survive all this torsion and shock, and bit-makers are interested because they want to design better bits.

Industry joined us in attempting to model this system mathematically. Five companies, plus Sandia, are investing money in this research. A private company (Jordan, Apostal, & Ritter Associates) does the modeling in conjunction with Sandia. We test the models in our vibration test facilities (Figure 9). A final test of the model will consist of using an instrumented drill string on an actual drilling operation by a major company.

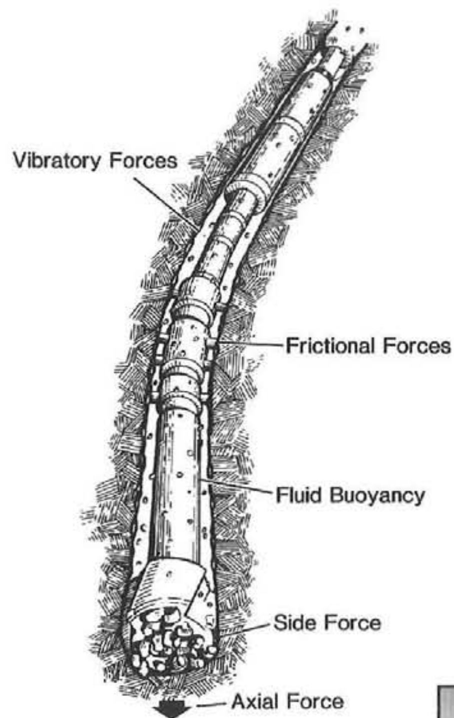


Figure 8
The drill-bit and bottom assembly bounces, twists, rubs, and vibrates during drilling. Modeling research is helping us develop an understanding of these forces to allow better-designed drilling systems and the development of downhole instrumentation.

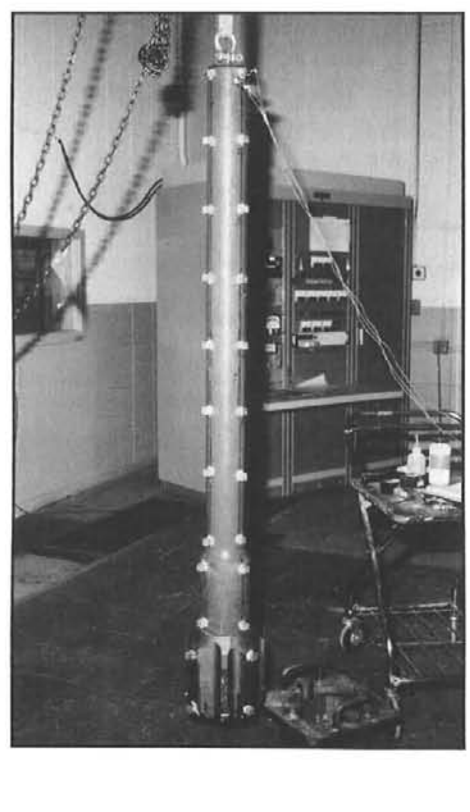


Figure 9
Mathematical models of drill-string dynamics are evaluated in our environmental testing facilities. An actual drill string is instrumented and then subjected to various forces and vibrations. The measured response is used to upgrade the models.

Diagnostics Technology

What is the downhole temperature? What is the shape and condition of the borehole? What kinds of rocks and soils are in the formation? The oil and gas industry normally uses logging tools to determine this kind of information. The tools are instrument packages from 5 to 20 cm in diameter and 3 to 24 m long. They are hung down the wellbore on a cable that has electrical connections to the surface. Sensors at the bottom of the unit measure temperature, pressure, and physical properties. The sensors are connected to electronic circuits downhole that gather data and send them to the surface where they can be interpreted in detail.

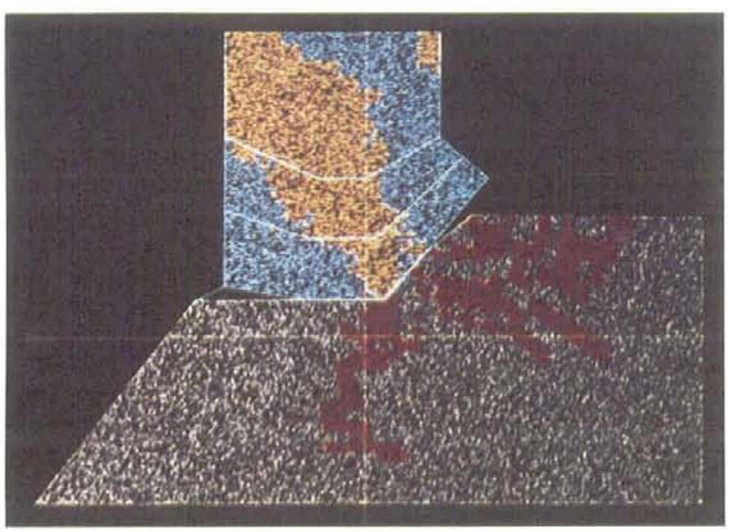
Industry's standard logging tools operate to about 100°C, well below geothermal drilling temperatures. Their electronics include standard printed wiring boards, lead-tin solder, and so on, all of which fail at higher temperatures. A number of years ago we combined forces with industry and universities to develop technology using radiation-hard devices we had developed in nuclear weapon work, thick-film hybrid circuits, and industry designs to build prototype tools (Figure 10). Now logging companies also have tools that work to about 225°C, with some capability to 300°C.

We are looking at special tools and special needs. For example, one requirement in drilling is a cement-bond log. Industry uses a tool that sends out an acoustic signal that penetrates the casing wall and the cement bond and bounces off the formation at each interface. We adapted this tool to high-temperature use. From the quality and timing of the signal we can determine whether cement is present between the casing and the formation, and to some extent the bond's quality. The problem with the electronics in currently available cement-bond tools is that the silicon-controlled rectifiers used for switching do not work at geothermal temperatures. Right now we are using a sprytron tube produced by EG&G. The tube has been improved to allow up to about 20,000 shots in a row, which is a desirable attribute.

BOX B

Bit Technology

Sandia has pioneered the development of drill bits using polycrystalline diamond compacts. Our effort involves analysis of structural properties, heat-transfer mechanisms, and fluid hydraulics around the bit. Extensive laboratory and field tests of bits using this technology have been conducted. Our results have been shared with private industry, which uses them to develop drill bits that are extensively employed in drilling oil, gas, and geothermal wells. Pictured are early designs from several bit manufacturers.



Computer-generated stress analysis of a drag bit cutting rock

BOX C

Instrumentation

Downhole instrumentation capable of operating in wells reaching temperatures of 300°C is needed by the geothermal industry. We have conducted research aimed at producing technology to meet these needs. Our effort has two foci: developing components capable of operating at such temperatures and finding ways to insulate components from that environment. Early research produced a number of hybrid components that could operate at high temperatures. More recent work has produced tools that are protected in Dewar flasks. An example is the acoustic borehole televiewer (Figure C-1). The basic idea was patented by Mobil about 20 years ago, and is used by several companies. To modify it for use in geothermal fields, we put in hybrid electronics, redesigned circuits, eliminated slip rings, and otherwise hardened it for high-temperature use. Tool electronics are contained in a Dewar. Acoustic transceivers are enclosed in a fluid that reaches formation temperatures. This tool has operated for several hours at 275°C.

By looking at the acoustic image, we can determine the structure of the wellbore. We demonstrated it at a site in New Mexico where Los Alamos National Laboratory was studying the extraction of energy from deep-underground hot-dry rocks. The tool provided a "picture" of the inside of the wellbore by processing the amplitude and travel time of a reflected acoustic signal. Figure C-2 shows a crack crossing a 3-m section of the wellbore diagonally. We also demonstrated it in some briny geothermal fields in the Imperial Valley. With our modified televiewer we were able to show the industrial operators that corrosion had eaten holes up to six inches in diameter in their casings.

Figure C-1
Acoustic borehole televiewer

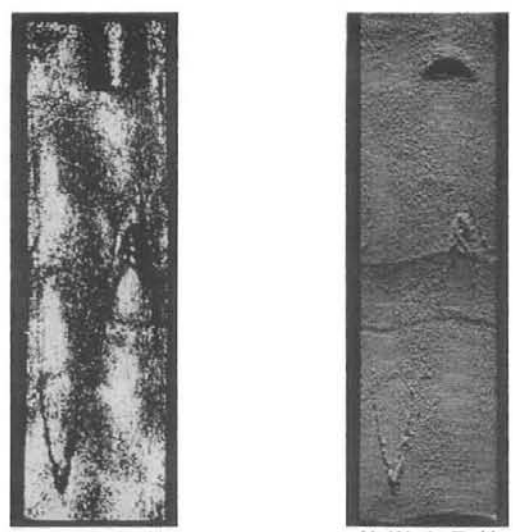


Figure C-2
Fracture mapping with the acoustic borehole televiewer

Figure 10
Borehole temperatures of 200°-300°C prevent the use of conventional logging tools for downhole measurements in geothermal wells. Sandia-developed radiation-hard electronics were combined with research from universities and designs from industry to build these prototype tools, which worked satisfactorily in an industrial geothermal well at 275°C.

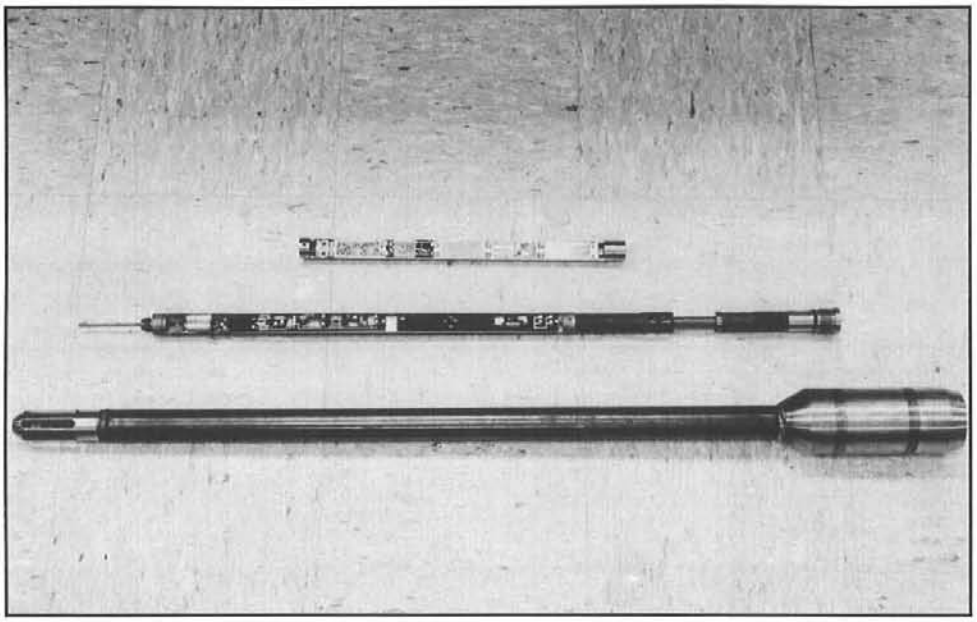
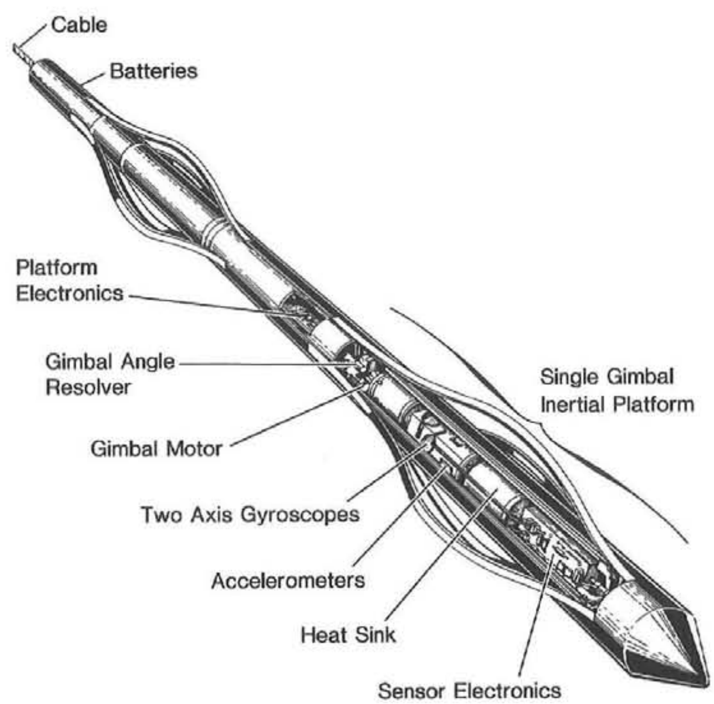


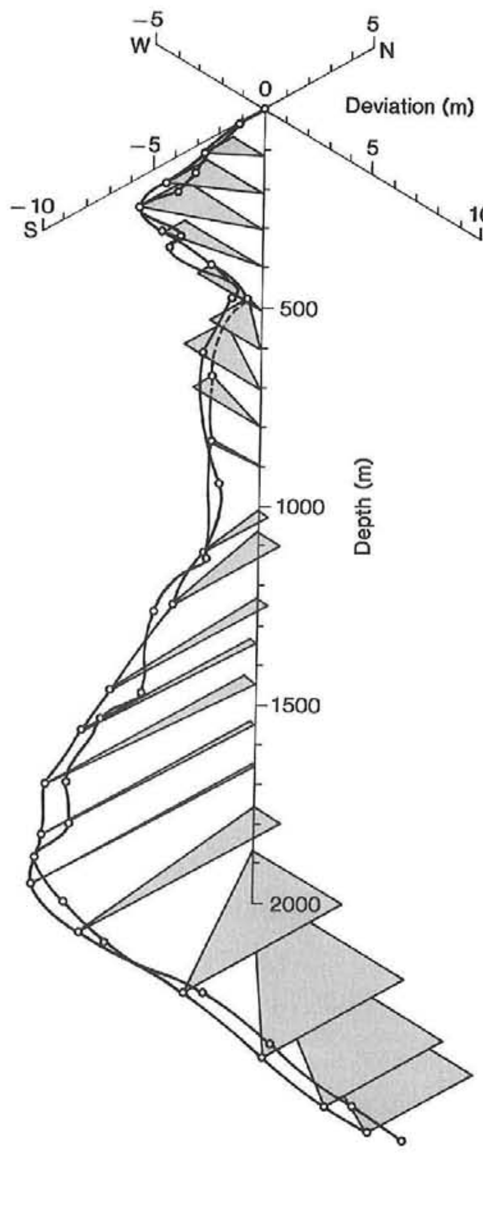
Figure 11
We have repackaged missile-guidance hardware to fit into a wellbore, with accelerometers and gyroscopes to give information on wellbore location. Data are upgraded using Kalman filtering techniques.



A prototype tool is being built for field evaluation.

An inertial navigator used in missile-guidance technology has been evaluated for use in mapping the exact location of a wellbore. Almost all offshore oil wells and some geothermal wells have deviated wellbores; i.e., they are drilled vertically to a certain depth and then branch off at some other angle. For instance, in the Geysers, stable land on which a drill rig can be erected is not necessarily where the production zone lies, so a hole has to be drilled at an angle from the vertical. The angle and direction must be well known if the hole is to intersect the reservoir. Those who drill offshore for oil and gas are concerned about potential well-location inaccuracies — for instance, drilling a relief well requires accuracies better than the current ± 3 m per 300 m of depth. We have developed inertial navigational systems that use gyros, accelerometers, and Kalman filtering for accurate measurements. To test this guidance system in a wellbore, we took a prototype (Figure 11) to Nevada and put it in a hole 15 cm in diameter and 610 m deep. On the first test we had an accuracy of about 0.9 m per 300 m. We are confident we can get to 0.3 m per 300 m. Industry is interested.

For more information, call Dick Traeger (505) 844-2155.



Results of directional logging of a hole using our new instrumentaion.

Geoscience Research Drilling Office

Researchers are now using the drill bit as a research tool to investigate the third dimension of the earth's crust. To help us understand processes occurring far beneath our feet, Continental Scientific Drilling Programs (CSDPs) have been established in the US and in other countries for the purpose of drilling deep into scientifically interesting regions of earth's crust to answer questions such as

- How is heat transferred from depth to the surface?
- What are the fluid dynamics in the crust?
- How are hydrothermal systems developed and maintained?
- When and where are minerals deposited?
- What are the fundamenal processes in volcanic eruptions?

At Sandia, the Geoscience Research Drilling Office was established to provide drilling, instrumentation, and engineering support to CSDP researchers—geologists, mineralogists, geophysicists, bacteriologists, water chemists, and gas chemists. The Geoscience Research Drilling Office is funded by DOE's Office of Basic Energy Sciences/Geoscience, as are the CSDP research projects.

The first geoscientific well drilled by Geoscience Research Drilling Office was in the Inyo chain of lava domes near Mammoth Lakes, California. There geoscientists studied heat and mass transport in near-surface magma by coring through a solidified magma conduit and a postulated dike that was thought to have fed the eruption sites. A coring operation from the top of Obsidian Dome (Figure 1) intersected the conduit 400 m below the surface, penetrated the conduit, and exited into the surrounding rock (Figure 2). Intact samples of rocks brought to the surface by the coring operation provided basic scientific data. Had rotary drilling been used, the rock would have been crushed and made useless for scientific purposes.

A similar coring operation located the postulated dike (Figure 3), verifying the hypothesis that magma had been fed to the string of lava domes and explosive pits in the Inyo chain by a single dike—a vertical crack—rather than by individual channels.

Another drilling effort given logistic support by the Geoscience Research Drilling Office was conducted to examine heat sources and dynamics in the Salton Sea, California. Nineteen off-shore shallow wells were drilled so that temperature measurements could be made to construct a thermal profile of the geothermal resourses in the Salton Sea area.

Logistic support was also given to a project at the southern end of Mammoth Lakes to explore the possibility of using geothermal heat to provide space heating for the city of Mammoth Lakes. This well also

◀ **Figure 1**
Drilling rig on the top of Obsidian Dome, Mono County, California.

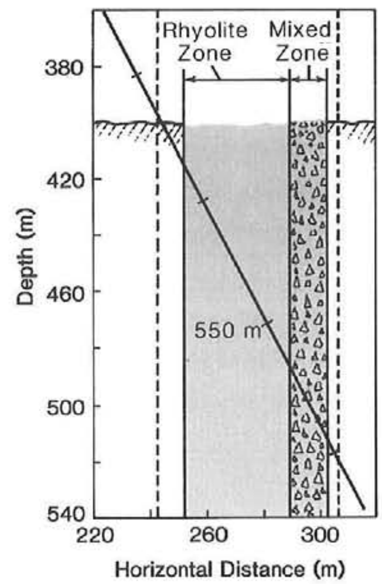


Figure 2
Sample of petrographic data from boreholes in the Inyo chain of volcanic formations.

provided fluid samples for geochemical research.

The most recent project supported by the Geoscience Research Drilling Office is the Sulfur Springs well drilled at La Cueva in the Jemez mountains (New Mexico). Here researchers have obtained continuous cores—long cylinders of intact rock—that are providing data to scientists interested in how hydrothermal systems deposit minerals such as copper, zinc, lead and molybdenum in the earth.

The Geoscience Research Drilling Office will continue to provide drilling and instrumentation support to scientists involved in CSDP research projects.

For more information, call Pete Lysne, (505) 846-6328.

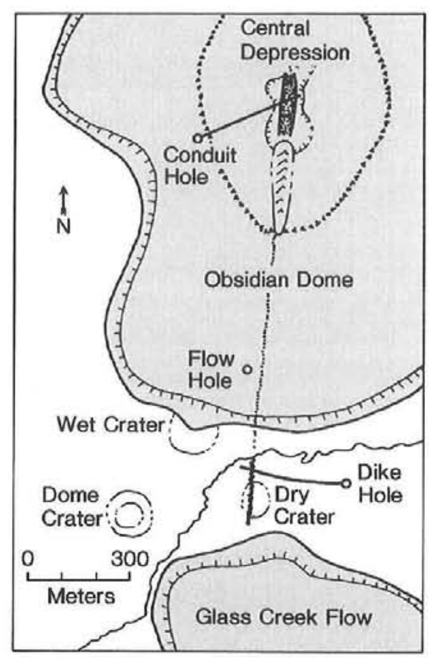


Figure 3
A plan view of operations near Obsidian Dome, California.

Exploratory Battery Technology

Although technologies for generating electrical power are well developed, scientific understanding of energy storage for later use is incomplete. We have a leading role in the nationwide attempt to improve this knowledge.

Government concern over US dependence on foreign and other unpredictable or exhaustible energy sources has led the Department of Energy to underwrite an effort by industry and federal laboratories to develop efficient energy-storage devices.

Sandia has been developing secondary* batteries for energy applications since 1978. Beginning with a small study group, we gradually increased our involvement until in 1982 we became the Lead Laboratory for DOE's Exploratory Battery Technology Development and Testing (ETD) project.

*Secondary batteries, based on reversible electrochemical reactions, can be recharged. Primary batteries–e.g., alkaline flashlight batteries–cannot.

Our goal is to develop new battery technologies in cooperation with industry. Specifically, the objectives are to develop and test electrochemical energy-storage systems that have high performance, low cost, long life, and high reliability for applications in electric vehicles, utility load-leveling, remotely located energy storage, and solar-energy storage systems.

Our approach in developing these batteries is to place contracts with industrial battery developers. We guide their work and evaluate their prototype units in our laboratories. We also undertake basic studies to resolve intractable problems that appear during development.

TABLE I Typical Battery Requirements

	Electric Vehicle		Utility	Solar	
	Fleet	Advanced	Load Leveling	Stand-Alone	Utility-Connected
Capacity (kWh)	20-40	20-50	100,000	100	25
Voltage (Vdc)	100	100-200	2000-3000	110	220
Energy Efficiency (%)	>70	>70	>65	>70	>70
Specific Energy (Wh/kg)	50	110	N/A	N/A	N/A
Specific Power (W/kg)	100	130	N/A	N/A	N/A
Energy Density (Wh/l)	80	140	30	N/A	N/A
Cycle Life	800	800	2000	2000	2000

TABLE II Applications for Selected Battery Technologies

	Stationary			Mobile		
	Utility Load-Leveling	CSOM* Load-Leveling	Solar	Electric Vehicle Fleet	Electric Vehicle Advanced	Electric Vehicle Vans
Zinc/Bromine						
Sodium/Sulfur						
Hydrogen/Nickel-Oxide						
Sealed Lead-Acid						

*Customer Side of Meter

The applications for which advanced secondary batteries are being developed fall in two general categories: mobile energy storage and stationary energy storage. Performance criteria for mobile applications are more stringent, while stationary applications generally require longer lifetimes (Table I).

Four advanced systems are of particular interest to us: zinc/bromine, sodium/sulfur, hydrogen/nickel-oxide, and sealed lead/acid. The first two have potentially broader applicability than the others (Table II).

The most mature of the technologies is sealed lead-acid. The hydrogen/nickel-oxide approach is being adapted from versions used in the aerospace industry. The zinc/bromine and sodium/sulfur systems are in early development and are the objects of intense R&D efforts. From a performance standpoint, the sealed lead-acid and hydrogen/nickel-oxide systems have been developed to a point closer to their potential limits than have zinc/bromine or sodium/sulfur; therefore, most of our development effort is oriented toward the last two (Table III). In the table, pertinent data for an improved lead/acid battery (similar in design to those used in today's automobiles but capable of deep-discharge operation) are also given for comparison.

TABLE III Characteristics of Selected Battery Systems

	Improved Lead-Acid[1]	Zinc/Bromine	Sodium/Sulfur[2]	Hydrogen/Nickel-Oxide[3]	Sealed Lead-Acid
Design:	Electric Vehicle	Electric Vehicle	Electric Vehicle	Stationary	Stationary
Development Stage:	Battery	Module	Cell	Battery	Battery
Energy Efficiency (%)	75	55	80+	85	80
Specific Energy: (Wh/kg)	42	75	165	65	38
Specific Power: (W/kg)	104	97	230	N/A	N/A
Energy Density: (Wh/l)	89	74	330	64	100
Cycle Life: (80% DOD*)	500	<200	>500	>700[4]	850

*DOD = depth of discharge

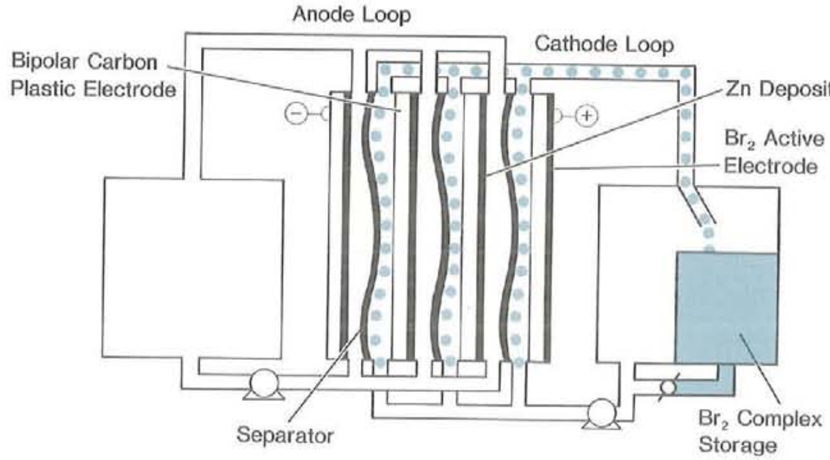
[1] For comparison

[2] Chloride Silent Power Limited cell

[3] Lightweight pressure vessel

[4] Test ongoing; est. life ~6k cycles

Figure 1
When the Exxon zinc/bromine battery is on charge, zinc is electrodeposited on the negative electrode and bromine is evolved at the positive electrode. The bromine reacts with the complexing agent to form an immiscible second phase. As the electrolyte is circulated, the second phase is swept from the cells into the catholyte storage tank, where it separates gravimetrically, as shown. On discharge, complexed bromine is carbureted into the catholyte flow stream, where it is returned to the cell. In the cell stack, the bromine complex is reduced and the zinc is oxidized. Separators are used in the cells to prevent direct chemical reaction of the bromine-rich stream with zinc.



Zinc/Bromine Technology

The zinc/bromine battery is a flowing-electrolyte bipolar electrode system that promises good performance at a projected cost as low as $75 per kilowatt hour. Most of the active materials are stored externally and are pumped into the power-conversion stack as needed (Figure 1).

In 1980, we contracted with Exxon Research and Engineering Company to begin developing this system. Exxon designed a cell (components of which are shown in Figure 2a) that consists of an extruded carbon-plastic bipolar electrode with an enhanced surface-area coating on its cathode side and an inset injection-molded flow frame. The flow frame contains channels for distributing both electrolyte streams. A microporous separator is also integrally molded into the flow frame. The end electrodes in the power-conversion stack serve as current collectors and contain embedded metal screens to increase their lateral conductivity. All external plumbing and storage tanks are plastic (Figure 2b).

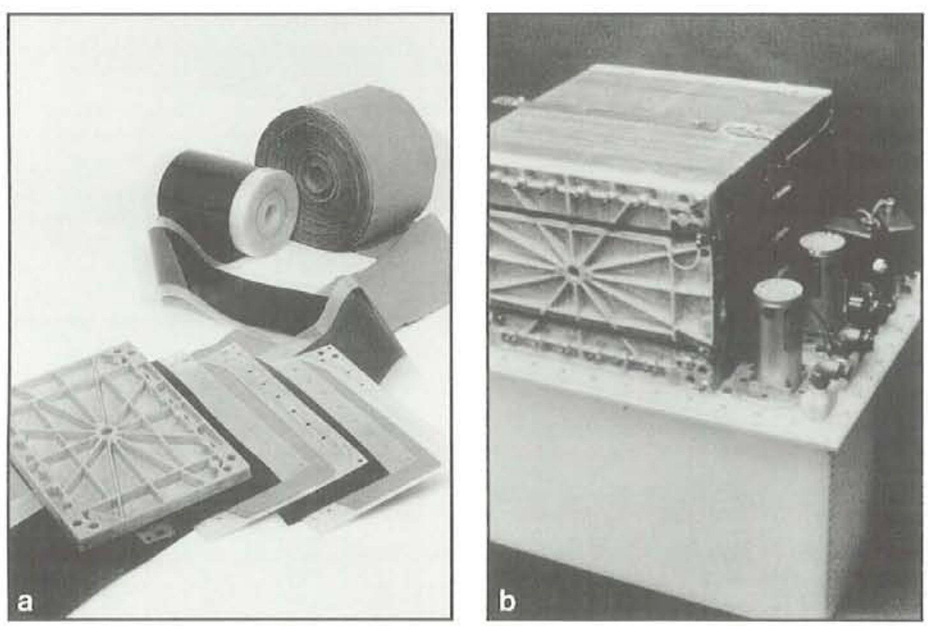


Figure 2
Exxon zinc/bromine components for a 1200-cm^2 cell were first produced in 1982. (a) Extruded electrode and separator materials are shown in the background; in the foreground are finished cell components. (b) The cells are stacked and mated to auxiliaries to form this complete 20-kWh zinc/bromine battery.

The development efforts at Exxon were aimed at mobile as well as smaller stationary applications. Tests on a 200-V, 15-kWh module indicated that the battery is capable of producing a specific energy of 75 Wh/kg, a peak power of 40 kW, and a specific power of 97 W/kg. Charge-discharge cycle life requires improvement, and the battery and its auxiliaries need to be engineered into a reasonably compact package. If these developments do not compromise its performance, this battery will then be ready to be evaluated for fleet (fixed-mission/regular-maintenance) electric-vehicle (EV) missions.

Exxon also built several small stationary batteries in the 10 to 20-kWh range. One 20-kWh battery achieved 178 cycles. A laboratory prototype 0.5-kWh battery achieved 2000 cycles in tests at Sandia. In June 1985, a 200-V, 30-kWh battery successfully powered an advanced ac-drivetrain experimental test vehicle at Ford Motor Company, the first advanced secondary battery to accomplish this.

The zinc/bromine system, like all flowing-electrolyte batteries, has the advantages that heat generated by electrochemical reactions is easily dissipated and that the electrolyte is easily renewed. The system suffers virtually no capacity loss with increasing cycle life. Since the battery requires periodic full discharge to prevent formation of zinc dendrites, cell equalization is not a problem. Flow batteries are, however, mechanically complex and are generally less energy-efficient than competing technologies.

While significant progress was made by Exxon in developing this system, additional work remains to be done. To address these needs, we placed a contract with Energy Research Corporation (ERC) to develop the core technology of the system (basic and supporting R&D, development and testing of auxiliaries, and qualification of materials) and to perform engineering and evaluation of a 50-kWh zinc/bromine battery module.

Work done under this contract will form the basis for a complementary effort under which ERC will build a 500-kWh load-leveling battery for the Electric Power Research Institute (EPRI). This unit is scheduled for evaluation at the Battery Energy Storage Test (BEST) facility in Hillsboro, New Jersey.

Sodium/Sulfur Technology

The sodium/sulfur system is a high-temperature advanced battery using a monopolar cell design. The anode is molten sodium and the cathode is molten sulfur. On discharge the cathode is held in an electrically conductive matrix material (carbon fiber or graphite). The chemically active electrodes are separated by a solid-ceramic electrolyte (sodium beta″-alumina)* that conducts sodium ions. Cells are connected in series-parallel arrays. Operating temperature is 300-350°C.

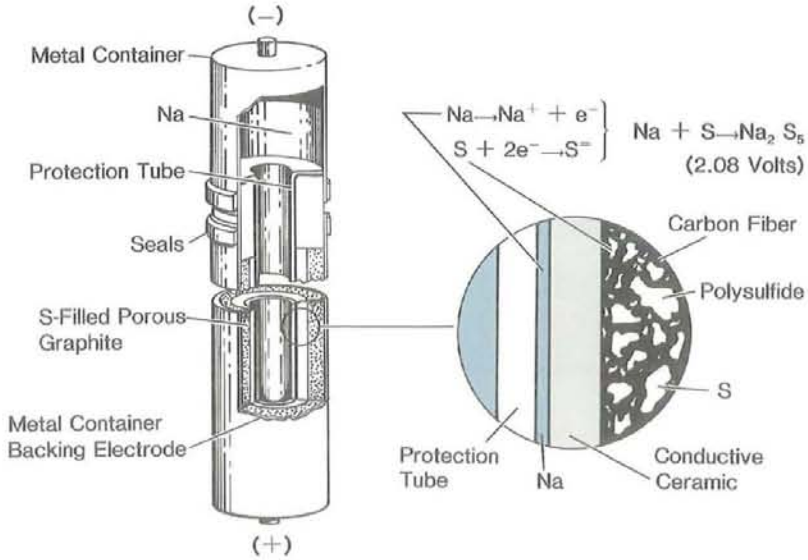


Figure 3
The sodium/sulfur cell design used by Ford employs a right circular cylinder with a sodium reservoir at the top and sulfur at the bottom. This is called a sodium-core cell, because the sodium is inside the beta″-alumina tube. A protection tube is placed inside of and close to the ceramic electrolyte. Its purpose is to meter the amount of sodium that could be exposed to molten sulfur if the electrolyte were breached; the temperature rise due to exothermic reaction between sodium and sulfur must be kept below 100°C. The sulfur is held in a carbon-fiber or felt matrix to facilitate electron flow through the cathode material. The beta″-alumina is sealed to an alpha-alumina header that acts as the anode/cathode insulator and the seat for the cell seals.

*The double prime indicates a specific crystalline structure.

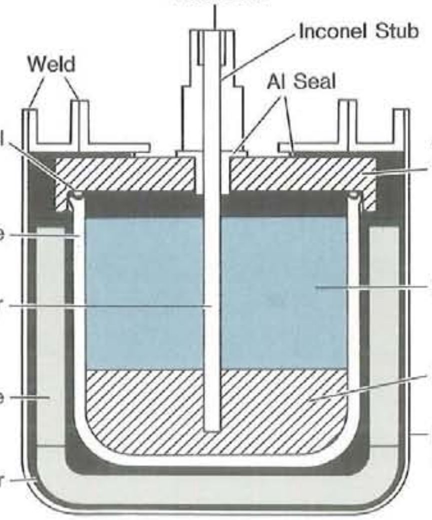


Figure 4
The sodium/sulfur cell design used by CSPL differs from that employed by Ford. The cells are generally smaller, with a capacity of 15 Ah, specific energy of 165 Wh/kg, and specific power of 230 W/kg. While this cell is also a sodium-core design, it does not incorporate a protection tube within the electrolyte as does the Ford cell.

We have technically managed a multi-year contract between DOE, Ford Aerospace and Communications Company (FACC), and Ford Motor Company to develop this system. We engaged other firms for supporting work, primarily on the beta″-alumina ceramic electrolyte. We have a number of in-house projects to undertake exploratory cell evaluation and to solve problems of electrolyte failure, cathode contamination, and freeze-thaw stresses. We intend to address the thermal-management issue in cooperation with industrial developers.

During the design effort, we developed a thermal model for sodium/sulfur batteries. Application of this model significantly affected the design of prototype EV units. We also characterized the physical, chemical, and mechanical properties of the beta″-alumina ceramic electrolyte. The model enables us to evaluate electrolytes from other developers as well as to improve processes and materials.

FACC developed cells ranging from 40 to 1500 Ah, the smaller for an EV-battery cell and the larger for a stationary energy-storage battery. Figure 3 shows the FACC cell design. A specific energy of 165 Wh/kg and specific power of 230 W/kg were demonstrated using the smaller single cells. A battery made up of these cells would be rated at about 95 Wh/kg. Extrapolation of data from these cells to a battery indicate that the system could satisfy fleet EV requirements. Cell lives in excess of 500 cycles are routine, and some have lasted over 1000 cycles. Further improvements in cycle life and cell reliability are needed, however, before the system can be used to support advanced EV battery applications.

A 100-kWh experimental battery, comprising four 128-cell modules, became operational at FACC in February 1981. Although one module was removed after 105 cycles, the remaining three operated for 32 months, achieving 675 cycles. At the end of the test, about 60% of the cells were still operable.

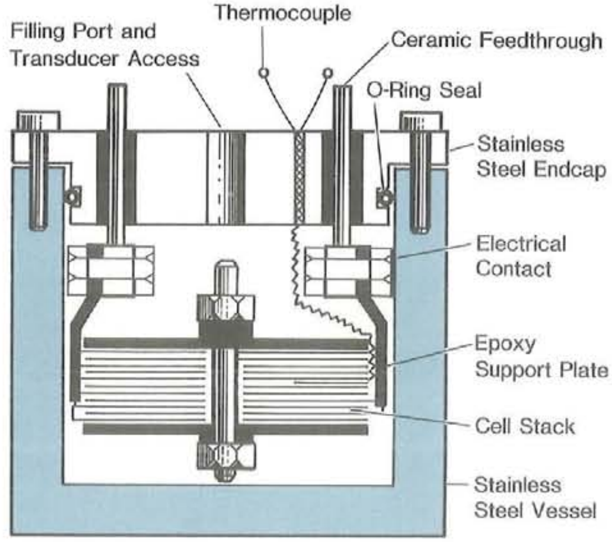
When DOE's contract with FACC expired, several important technical issues remained unresolved. Improvements were needed in durability of the ceramic electrolyte, corrosion resistance of the sulfur containers, cell reliability, and freeze/thaw survivability. In addition, it became necessary to develop and evaluate a large battery to encourage commercialization of the technology.

In response to these needs, we have placed a multi-year development contract with Chloride Silent Power Limited (CSPL). Tasks include development of the core technology of the sodium/sulfur system (electrolyte research and development, material development and qualification, cell development, cell testing and post-test analysis, and module testing), and engineering of a battery intended specifically for stationary energy storage (a 50-kWh module). Then, under contract with EPRI, CSPL will use the work we initiated to design and build a 500-kWh battery to be tested in FY89 at the New Jersey BEST facility.

The small, cost-effective cells developed by CSPL (Figure 4) are projected to have high reliability and to be capable of surviving numerous freeze/thaw cycles. Eventual cost is expected to be $90/kWh.

EV applications require compact batteries capable of generating high specific energy and high specific power, and an energy-to-power ratio of 1:2 is desirable. The sodium/sulfur system meets most of these requirements and, therefore, seems to hold the greatest promise for EV applications.

Figure 5
In the hydrogen/nickel-oxide system, nickelic hydroxide is reduced on discharge to nickelous hydroxide. The hydrogen is oxidized to water during discharge and is reformed by electrolysis during charge. A hermetically sealed pressure vessel contains the hydrogen, the pressure of which serves as a built-in state-of-charge indicator.

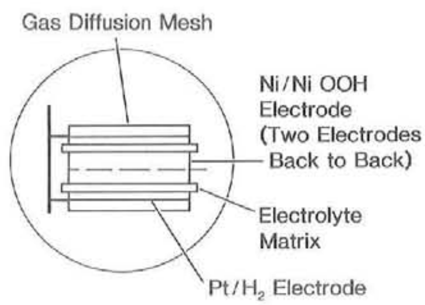


Hydrogen/Nickel-Oxide Technology

The hydrogen/nickel-oxide system has been successfully used in the aerospace industry, where it is usually configured as single hermetically sealed cells, each of which has a very long life, requires no maintenance, and is very expensive (about $25,000/kWh). We are interested in the system because of its long life (more than 6000 cycles), tolerance to abuse, and very low maintenance and are focusing on reducing system costs to our program goal of $375/kWh. At present, the system's costs are comparable on a life-cycle basis with other advanced battery systems being developed for stationary applications.

In 1983, we initiated a program with COMSAT Laboratories to reduce the cost of the system without sacrificing its performance characteristics. COMSAT in turn subcontracted with Johnson Controls, Inc., because of that company's expertise in cell-component fabrication and its experience with nickel/zinc batteries.

A schematic diagram of an experimental hydrogen/nickel-oxide



Cell Detail

cell is shown in Figure 5. The positive-electrode reactions of hydrogen/nickel oxide batteries are similar to those in nickel/cadmium systems.

The design selected by the COMSAT/JCI team was a "prismatic" (noncylindrical) multicell battery contained in a common pressure vessel (Figure 6). This alone substantially reduced projected system costs. Nominal cell voltage is 1.3 volts, and charge capacity is usually measured down to 1.0 volt. To demonstrate the great flexibility of this technology, JCI recently fabricated a 12-V, 2.5-Ah battery. This direct scalability is unique among advanced secondary batteries.

Compared to other batteries, the hydrogen/nickel-oxide system performs very well at low temperatures. Recent tests showed that, at -40°C, capacity to 1.0 V/cell was about 75% of room-temperature capacity. Discharge voltage is depressed at the low temperature, but there is no loss of capacity.

COMSAT estimates that the energy density of the 100-Ah battery will approach 65 Wh/kg, and energy per unit volume will be 64 Wh/liter at the end of development. These values should be higher for larger systems. A 15-kWh system is contemplated, and a decision on whether to proceed with its development will be made. If evaluation is encouraging and if costs can be reduced by an additional factor of 3 to 4, the battery may prove useful in solar electric applications.

This battery system has high initial costs, but maintenance costs are low to nonexistent. Because of these factors and its long cycle life, the system is a good candidate for long-period use in remote areas (e.g., by the Forest Service).

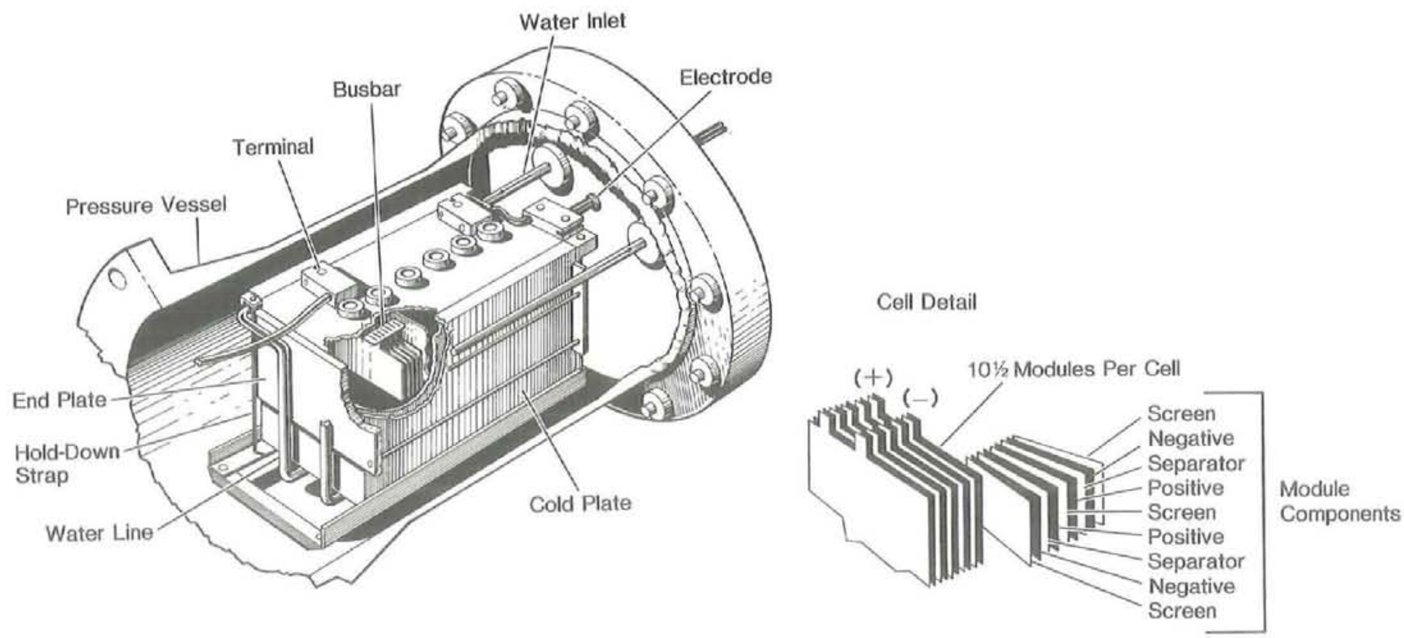


Figure 6
A six-cell hydrogen/nickel-oxide battery is shown in a reusable pressure vessel. The negative electrode consists of a current collector with a catalyst on the front face and a water-repellent membrane on the back. The positive electrode is a sintered nickel plaque impregnated electrochemically. Twenty-one 12.7 cm x 12.7 cm positive and negative electrodes are assembled to make a single cell with a nominal capacity of 100 Ah.

A standard polypropylene case is used for the six-cell battery, with the cells connected through the wall of the case. Gases generated on overcharge and overdischarge are recombined.

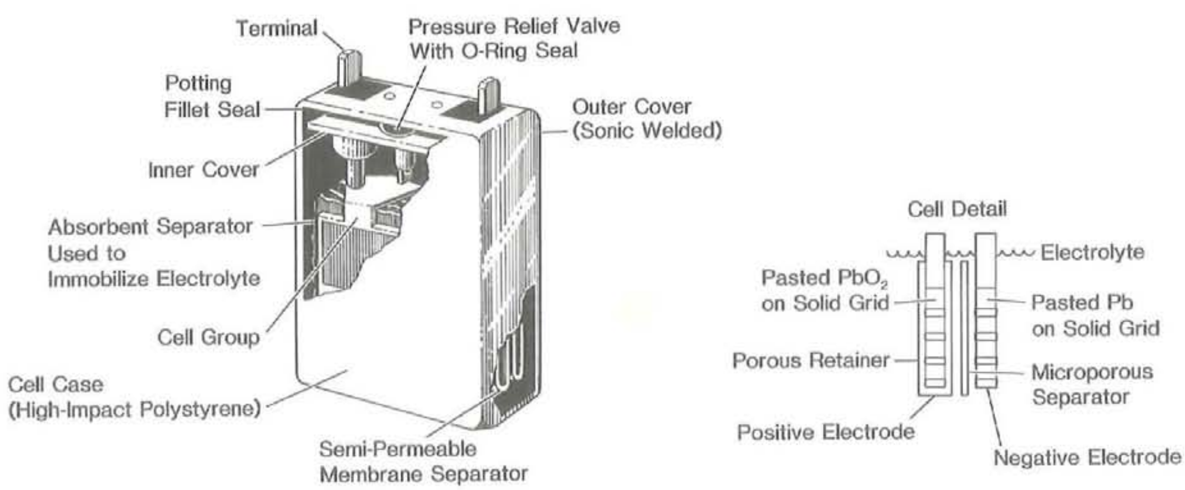


Figure 7
In sealed lead-acid systems, the electrochemical reaction is the same in both flooded- and starved-electrolyte cell designs. In the latter case, the electrolyte is held in a saturated fiber that permits migration of oxygen gas. Thus, oxygen formed on overcharge at the positive electrode can reach the negative electrode, where it reacts with lead and sulfuric acid, forming lead sulfate and water. As long as the charging rate is at or below the recombination rate, water loss (and hence maintenance) is virtually eliminated. Immobilization of the electrolyte also reduces the need to overcome electrolyte stratification through overcharging of the battery, a procedure regularly required in flooded cells. This results in improved performance when the battery is operated in a partial state of charge, as might occur in solar applications.

TABLE IV Summary of Battery-System Development

System	Advantages	Development Status	Challenges
Zinc/Bromine	• Low cost	• 120-V, 20-kWh SES battery built • 200-V, 30-kWh EV battery built • Electrodes are 1200 sq. cm. • 8-cell stack nearing 1500 cycles	• Material durability • Stack sealing • Battery reliability • Battery efficiency
Sodium/Sulfur	• Performance • High efficiency	• Effective cells designed • Cells with good perfomance built • High-quality beta″-alumina produced • SES and EV batteries demonstrated	• Cell production costs • Electrolyte durability • Freeze/thaw survivability • Thermal management
Hydrogen/ Nickel-Oxide	• Low maintenance • Long life • Tolerance to abuse • Low-temp. perf.	• Prismatic cell developed • 6-cell, common pressure vessel configuration used • Cost reduced by factor of 12	• Battery cost
Sealed Lead-Acid	• Low cost • Proven perfomance	• Batteries are commercially available • Nominal capacities range from 100 to 1000 Ah	• Performance credibility • Deep-discharge cycle life

Sealed Lead-Acid Technology

The lead-acid battery, because of its wide commercial availability, is considered a baseline system against which advanced secondary batteries are compared. However, maintenance required by the flooded deep-discharge design makes this system unacceptable for many applications.

In 1980, we contracted with Eagle-Picher Industries and Gould Laboratories to extend the then-existing sealed, maintenance-free battery technology from standby to deep-discharge solar cycle service. With our guidance, sealed cells were designed and fabricated (Figure 7).

We were able to demonstrate battery lives of more than 1000 deep-discharge cycles in testing that simulates solar applications. GNB Batteries, a corporate spinoff from Gould, is now making sealed lead-acid batteries available commercially. We have sent one of them to a test site in southern New Mexico for evaluation under field conditions. The site provides a stand-alone test bed, with a photovoltaic array providing electricity to charge the battery.

Summary

The four systems described above are representative of several we have worked on. Other systems we have examined, though at a lower level of effort, include zinc/chlorine, iron/chromium redox, zinc/ferricyanide, and lithium/metal sulfide. When the systems now under development meet performance goals, we will turn our attention to more speculative systems such as ambient-temperature lithium or metal/air.

From a performance standpoint, the sealed lead-acid and hydrogen/nickel-oxide systems are approaching their performance limits. The zinc/bromine system is somewhat more speculative, while the sodium/sulfur system has not progressed much beyond the cell-engineering stage. These two systems, however, are receiving a great deal of attention, and it is expected that the pace of their development will continue to accelerate (Table IV).

The primary challenges we face with the zinc/bromine system involve engineering of the battery stack and associated components into a reasonably compact and workable package. Challenges associated with the sodium/sulfur system include cell-production techniques and costs, electrolyte durability, freeze/thaw survivability, and thermal management. The ongoing challenge presented by the hydrogen/nickel-oxide system is cost reduction. Sealed lead-acid, a mature technology, has only to demonstrate consistent deep-discharge performance to become a commercial success.

In short, there is no clear winner in the race for the ultimate rechargeable battery. Each system has some advantages such as performance, cost, or durability, but no system has them all, and each advantage is offset by technical problems that require additional development work to resolve.

With the programs we have laid out, and with DOE support, we can bring these technologies to relatively full maturity. Depending on economic conditions and the status of competing energy sources, we should witness the successful transfer of these technologies to private industry by the early 1990s.

For more information, call Nick Magnani (505) 844-3475.

Solar-Energy Programs

Our solar-energy research programs are producing innovations that may make solar technologies competitive with conventional electricity in the 1990s.

Advanced research being conducted at Sandia is an important factor in the rapid progress of solar and wind technologies. Although solar-produced power is not economically competitive on US utility grids, technological advances (assuming continued funding) are expected to reduce costs significantly within a decade, making these alternate energy sources important contributors to increased electric power demands beyond the 1990s.

Four principal technologies for converting sunlight into electricity are

- Central Receiver Thermal Conversion — an array of sun-tracking mirrors (heliostats) that concentrates thermal energy from sunlight onto a large receiver atop a tower, producing high temperatures that convert water to steam for driving electric turbines.

- Distributed Receiver Thermal Conversion — parabolic dish or trough concentrators, each with a thermal receiver at its focal point that heats a high-temperature circulating oil. The heated oil is then pumped to a heat exchanger that produces steam which in turn drives a turbine. An alternate approach is to locate a small heat engine and generator at the focal point of each dish to avoid plumbing and heat-transport losses.

- Photovoltaics — a way of converting sunlight directly into electricity by means of solar cells.

- Wind Power — wind turbines, either vertical axis or horizontal axis, connected to a generator that produces electricity to be fed directly into the utility grid.

We have research programs in each of these areas that deal with the production of either electricity or high-temperature thermal energy. Our largest efforts are in the central-receiver and photovoltaic programs.

Central Receiver Technology Program

Solar thermal central receivers have been under development since the early 1970s. The first systems employed water or steam in the receiver as the heat-transfer fluid, although liquid sodium, molten salts, and hot air have been evaluated. We are extensively testing and evaluating molten salts, which seem to have the greatest potential for efficient heat transfer in next-generation systems.

Two major facilities are engaged in central receiver work: the 5-MW_t Solar Thermal Test Facility (STTF) in Albuquerque, and the 10-MW_e Solar Central Receiver Pilot Plant ("Solar One") near Barstow, California.

Solar Thermal Test Facility

The STTF (Figure 1) is located about 13 km southeast of Albuquerque on Kirtland AFB. A field of 222 individually guided heliostats provides 8214 m^2 of reflecting surface, redirecting sunlight onto the receiver at an average concentration of 250 suns, with a peak of 600 suns (1 sun = 1 kW/m^2).

When built in 1977, the CRTF was a test facility for major components being considered for use at Solar One. Since that time we have used it to test advanced receivers for different technologies ranging from Barstow's pressurized water/steam type to those employing molten salt or liquid sodium and a Brayton-cycle, hot-air jet-engine receiver.

A recent major activity at the STTF was the Molten-Salt Electric Experiment (MSEE).* The MSEE was a full-system demonstration of molten-salt solar technology and the first solar central-receiver project in the US to use this heat-transfer medium to convert solar energy to electricity. We were the technical managers for a consortium encompassing government (DOE), industry, the utilities, and the Electric Power Research Institute of Palo Alto, California. Our experiments have established that molten nitrate salt (60% $Na_2 NO_3$ and 40% $K_2 NO_3$) is an efficient working fluid for generating electric power at temperatures near 540°C. We think molten-salt systems represent the next generation of technology for central-receiver applications, and any future larger-scale pilot plant would likely use molten salt or a combination of a hybrid liquid-sodium receiver and molten-salt thermal storage.

Since 60% of a central receiver plant's total capital cost is for heliostats, we use the STTF in an intensive R&D effort to reduce the price and improve the efficiency of heliostats. We track the sun with them, occasionally focusing the beam from one of them onto a test panel on the tower. We then profile

*See "Molten-Salt Electric Experiment," *Sandia Technology*, Vol. 9, No. 4, December 1985.

Figure 1
Our Solar Thermal Test Facility supports technology development and contains test facilities for central and distributed receivers, a solar furnace, and related test capabilities.

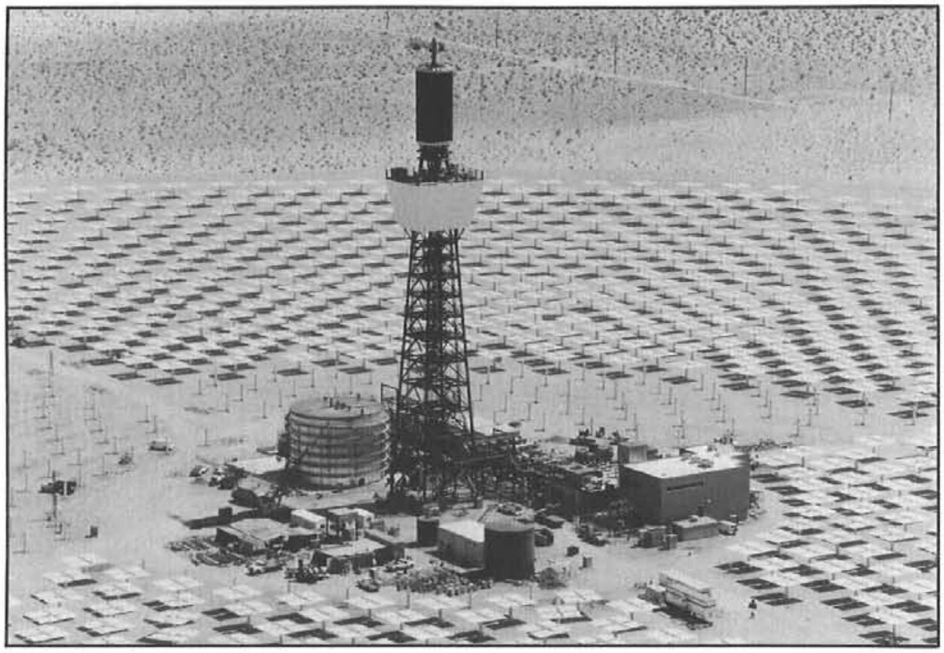


Figure 2
The Solar One central receiver power plant is located at Barstow, California. This 10-MW_e pilot plant is undergoing sustained power-production testing.

that beam to see how well the heliostat is focused, the degree of its reflectivity, and the accuracy of its tracking. We will continue to evaluate advanced heliostat designs as they become available from manufacturers.

We are also looking into the use of stressed membranes as heliostats. These will consist of a membrane stretched across the sides of a large tubular or metal-channel ring. One side serves as the reflector, and the other side encloses a volume between the two films where a slight vacuum will cause the front film to curve, focusing the reflected sunlight.

Solar One

Solar One (Figure 2), the world's largest solar electric generating station, is performing as designed. Under our Livermore Laboratory's technical management, this pilot-scale plant is a cooperative effort between government and industry to evaluate the technical feasibility, economic potential, and environmental acceptability of the solar thermal receiver concept. The project is located near Barstow in the Mojave Desert on a square kilometer of land owned by the Southern California Edison Company.*

After supplying its own power needs, the Barstow plant is designed to produce at least 10 MW_e for Southern California Edison's grid for 8 hours on the "best design day" (summer solstice). The worst (winter solstice) and best design days are based on insolation conditions developed from on-site measurements. The plant's capability and electrical output depend on sun and atmospheric conditions. During certain periods of the year, the plant's energy conversion capability, using supplementary heat from storage, can exceed the 12.5-MW_e turbine-generator rating.

Solar One's design was made possible by technical advances over the last ten years in computers and software. We have used this technology to write advanced computer codes that simulate and evaluate the performance of solar central-receiver systems and their components. Another area benefiting from computer advances is plant operation. The plant now needs numerous workers to operate it, but current work on advanced control systems is aimed at significant reduction in personnel.

In the solar central-receiver concept, thermal energy can be extracted immediately and converted to electricity or stored for use as required. In fact, the storage capability of the central-receiver system is one of its major features: energy can be stored to extend plant operation. Solar One's thermal storage capacity ranges from "buffer" storage over short periods—e.g., when clouds block the sun—to longer-term storage for up to six hours.

*See "Solar One Reaches Milestone," *Sandia Technology*, Vol. 9, No. 2, June 1985.

Distributed Receiver Technology Program

We have been involved in this program since 1974, testing and evaluating collectors from several manufacturers, as well as designing improved systems and components to be made available to industry. Two types of collectors are used in the distributed receiver concept: sun-tracking parabolic dish concentrators and parabolic trough-shaped concentrators. In both systems, a circulating fluid is heated at the collectors and pumped to a heat exchanger where its thermal energy is used to produce steam for driving an electricity-producing generator.

Parabolic Dish Concentrators

One of the earliest examples of dish thermal technology is Georgia Power's Shenandoah project, a planned community south of Atlanta. The system is made up of 114 parabolic dishes manufactured by Solar Kinetics of Dallas and produces 400 kW of electricity and process heat for a knitwear factory.

A limitation on this approach is the cost and relatively large thermal losses that occur in gathering thermal energy from the focal point of each dish and transferring it through the insulated plumbing system to a central point. One promising technology we are looking into is chemical transfer of this energy. Chemical reactions can be used at the receiver to capture thermal energy in the form of decomposition-reaction products that can then be transported to the point of use. There they can be recombined in a catalytic converter and the heat recaptured that was used to separate the constituents in the first place.

The requirements for such a system are that the reactions be facilitated by catalysts so reaction products can be transported together back to the point of use. The reaction products do not recombine until they are in the proper temperature and pressure environments in the presence of a catalyst. The reactants can be transported in either direction at ambient temperatures, making pipe insulation unnecessary. Basically, the system is a chemical heat pipe in which heat is injected at one end and extracted at the other, with the reactants at low or ambient temperature between the ends. We are performing closed-loop laboratory experiments on methane reforming and have begun designing a scaled-up outdoor thermal-transport experiment.

We have been looking into the "dish-electric" approach, which involves placing a heat engine at the focal point of a dish and generating electricity there. The most successful of these devices has been the Stirling engine; it has achieved a 30% solar-to-electric conversion efficiency at Rancho Mirage, California. We are installing organic Rankine (conventional steam-turbine) and Brayton-cycle (jet) engines (Figure 3) at the STTF to continue evaluation of other conversion technologies.

An innovative approach to thermal-to-electric conversion being pursued at Sandia is the liquid-metal thermoelectric converter, a direct-conversion device using liquid sodium or mercury that is forced through a selective ionic conductor (beta″ alumina) by heat and pressure.

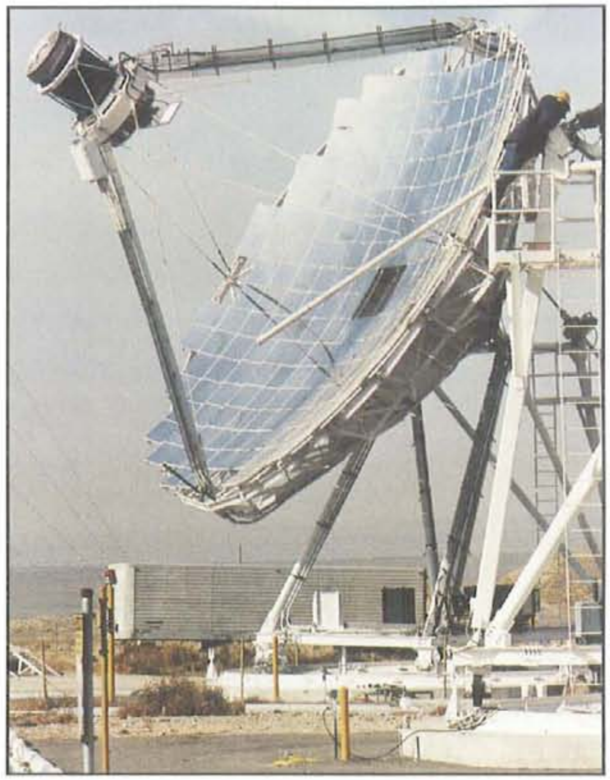


Figure 3
Testing an organic steam-turbine engine generator at the focus of a parabolic dish concentrator in the Solar Thermal Test Facility.

Parabolic Trough Concentrators

Parabolic trough collectors are products of a technology that has matured considerably over the past decade. Although a number of trough systems are in operation around the country, only a few have been built wholly with commercial financing. We consider the technology to be well-established in both performance and cost.

Today parabolic trough facilities can produce thermal energy for an overall cost of between $10 and $15 per million BTU. Although the cost is still not competitive, our goal is to keep the technology viable until the energy situation changes to the point that trough technology becomes useful. Meanwhile, we will evaluate design advances in reflectors and materials from other areas of the solar thermal program for incorporation into the parabolic-trough technology. At present, we use the STTF as a test location for evaluating trough hardware from four manufacturers.

Photovoltaics

Photovoltaics, currently the most rapidly developing solar-power technology, is blossoming into a substantial industry. The 180% increase in the sale of photovoltaic products worldwide in 1984 demonstrated their ability to provide electric power for specialized applications. Even more impressive is the fact that the world market for photovoltaics in 1985 was about 25 MW, compared with 4 MW in 1982, at a price of about $10 a watt. However, this was all for special applications: consumer products, and remote radios, water pumping systems, diesel/electric replacement, etc. The photovoltaics industry has provided many small- and intermediate-size systems, along with several large utility grid-connected systems that do not yet furnish a significant percentage of the world's energy requirements.

We support DOE's program of introducing photovoltaics into the commercial market. Three photovoltaic approaches that show potential for being competitive with fossil fuels are

- Flat-plate collectors (both tracking and fixed) using crystalline silicon,
- Flat-plate collectors using advanced thin films such as amorphous silicon,
- Tracking concentrator collectors.

Photovoltaic cells, usually made of crystalline silicon, convert sunlight directly into electricity. When photons strike the cell, electrons are freed from silicon atoms. These free electrons are then drawn off by a grid of metal conductors, producing a flow of direct current. The basic modules of solar electric systems are groups of photovoltaic cells mounted onto a rigid plate and wired together (Figure 4). Some advantages of solar cells over conventional electricity sources are that they require no fuel, are self-contained, have no moving parts, are nonpolluting in operation, and require little maintenance over a

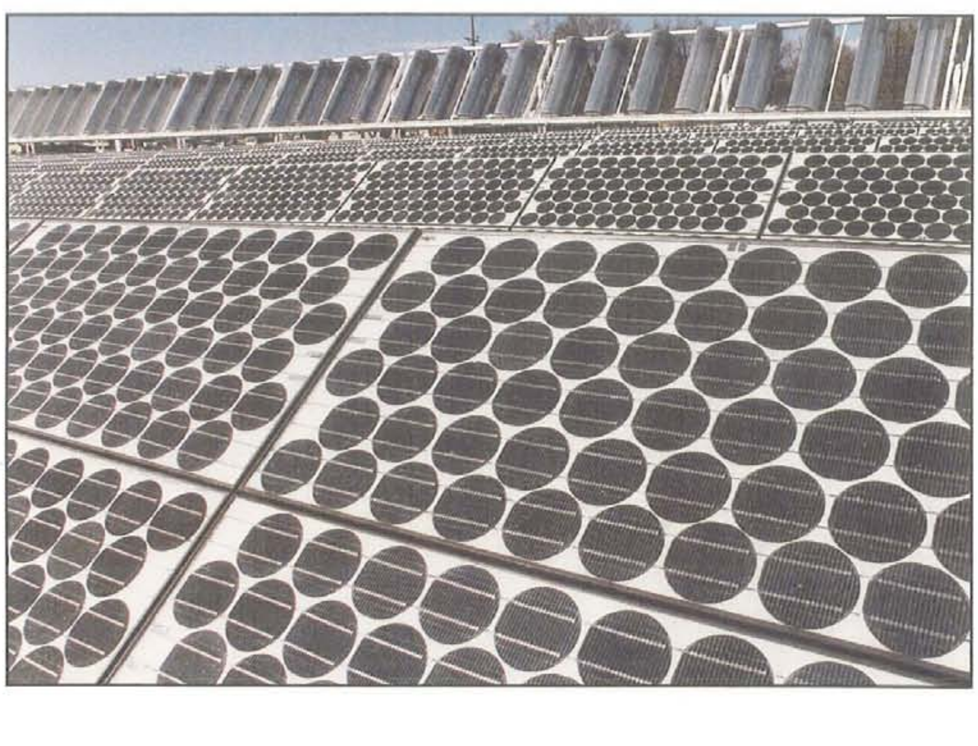
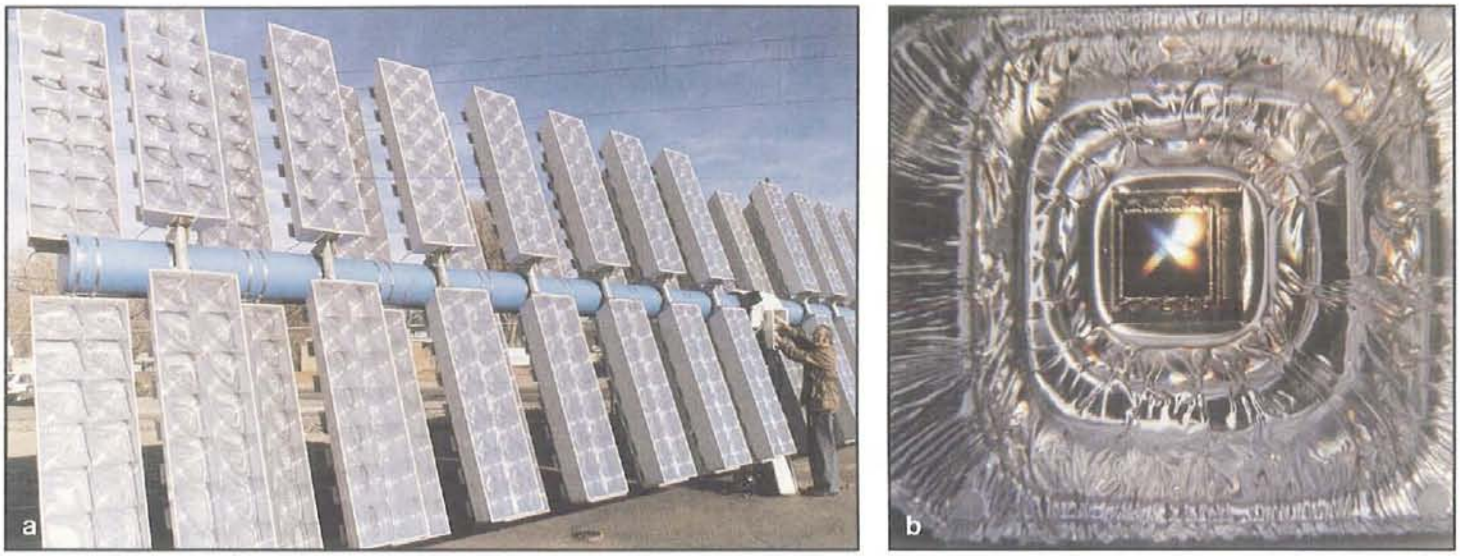


Figure 4
Modular-array building blocks of crystalline silicon photovoltaic modules being evaluated. This work emphasizes the defining and testing of low-cost foundation, structure, wiring, and safety concepts for power systems.



lifetime of 20 years or more.

Residential applications are a potentially important area for photovoltaics, and we have a number of ongoing experiments to evaluate the performance of rooftop collectors. We are looking at mechanical insulation approaches, thermal effects of insulated collectors on the roof, module supports, electrical equipment inside the house, and safety and installation considerations.

We are also evaluating power-conditioning equipment that converts dc electricity produced by a photovoltaic array into ac. The principal concern with power conditioning is cost, reliability, and the quality and safety of the power produced. All the units we test have been developed commercially for photovoltaic applications. It is difficult for individual suppliers to adequately test power-conditioning equipment because few of them have the necessary specialized equipment (such as photovoltaic arrays).

Concentrator technology is another photovoltaic approach that has the potential to provide reliable commercial electric power at a cost competitive with conventional sources. Concentrator systems use specially designed lenses to focus up to several hundred times more energy onto a cell (Figure 5).

In concentrator photovoltaic technology, we seek to replace expensive cell material with inexpensive concentrating optics. In addition, we benefit from the fact that cell efficiency improves in high-intensity sunlight. At 100 suns, today's most efficient silicon solar cell will convert over 28% of the sunlight it receives to electricity.

In concentrator photovoltaic research, we are also pursuing advanced cell technologies that theoretically can achieve efficiencies greater than 30% (typical of thermal cycles), and perhaps nearly 40%. Among semiconductor materials we are looking into are gallium arsenide and aluminum gallium arsenide (Box A). Multijunction, or "mechanically stacked cell," technology is more expensive than the other two cell materials but is feasible since cell material is usually less than 20% of overall system cost. In this approach, the high-bandgap cell at the top in Box A transmits long-wave light to the bottom cell. Most of our multijunction research is in this area. We are stacking various thin gallium-arsenide cells on silicon cells. We expect shortly to have a working demonstration of a 30%-efficient stacked cell. Such a cell can directly replace silicon cells in all the photovoltaic technologies we are exploring, making it unnecessary to design new optics and tracking systems.

Figure 5
Photovoltaic concentrator array (a) of point-focus Fresnel lens (b) is being tested in the Photovoltaic Advanced System Test Facility.

An exciting potential exists in our newest development— strained-layer superlattices.* These represent a brand-new class of semiconductor materials whose properties can be adjusted by controlling layer thicknesses, materials, and crystal orientations. This means that we can design optimum-bandgap materials for use in a multijunction structure. In the long term, this may provide the key to achieving even greater efficiency — perhaps more than 40%. We recently demonstrated the first p-n junctions ever assembled in a superlattice structure, using alternating layers of gallium phosphide and a gallium-phosphide material with 20% aluminum content.

*See *Sandia Technology* Vol. 10, No. 1, October 1986.

BOX A

Mechanically Stacked Multijunction Solar Cells

Mechanically stacking solar cells with different bandgaps provides a near-term approach to achieving multiple-junction high-efficiency solar cells. As illustrated in Figure A-1, the cells are separated by a transparent adhesive layer so that sunlight not absorbed by the top (high-bandgap) cell is passed to the bottom (low-bandgap) cell.

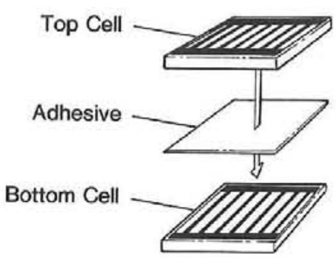


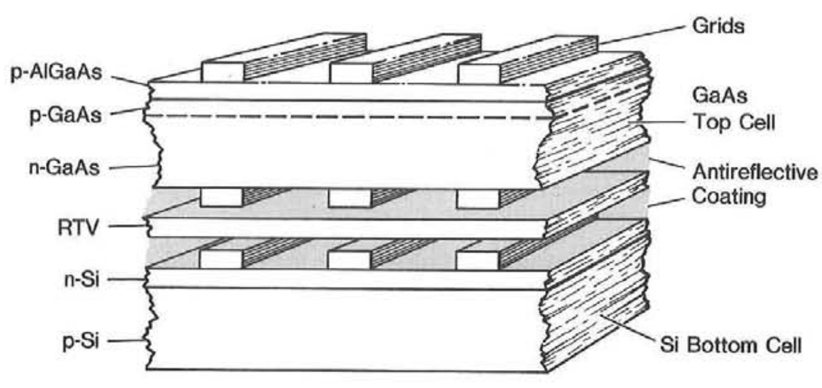
Figure A-1

We recently fabricated and tested a GaAs-on-silicon stacked solar cell. We obtained a "best ever" efficiency for a tandem multijunction solar cell of 26.6% at 300 suns concentration under a simulated spectrum. This high efficiency was achieved despite lack of optimization in several important cell parameters, including antireflection coatings, grid design, and cell thickness.

Figure A-2 is a schematic of the GaAs/silicon tandem cell. This cell, provided by Hughes Research Laboratories, had an antireflection coating and a grid on both the front and back surfaces to maximize transmission of below-bandgap photons to the underlying silicon cell. The cell was bonded to a concentrator silicon cell fabricated by Applied Solar Energy Corporation. The stacked cell was operated as a four-terminal device (i.e., the GaAs and silicon cells were electrically independent) since the cells are not current-matched and two-terminal (series) operation would have resulted in unacceptable losses.

Performance of the GaAs/silicon tandem cell as a function of solar concentration is shown in Figure A-3. This demonstration was to verify our modeling routines and establish the optical coupling requirements of a mechanically stacked device. We are also stacking a higher-bandgap AlGaAs cell on a silicon cell. This tandem cell will allow operation as a two-terminal as well as a four-terminal device, since the AlGaAs (1.7 eV) and silicon (1.1 eV) cells are current-matched in a standard 1.5 air-mass solar spectrum.

Figure A-2



Ongoing research should make it possible to fabricate "monolithic" cell stacks, eliminating the complexity of the mechanical stack and its attendant optical losses.

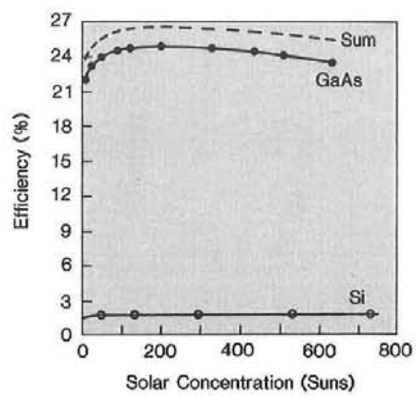


Figure A-3

Wind Power

Only 2% of the sun's radiant energy that reaches the earth is converted into wind. Yet, if efficiently harnessed, wind power could provide a substantial part of the US demand for electricity. Moreover, wind power, like other forms of solar energy, is renewable and nonpolluting (except for noise).

Wind turbines are of two basic types: horizontal-axis (HAWT) and vertical-axis (VAWT) which resembles an upside-down eggbeater. We have been working principally with the latter. We have developed aerodynamic and structural modeling codes that have helped us understand VAWT performance (Box B). We have designed, built, and successfully tested a number of experimental VAWT machines in the 17-m-diameter size. Our new initiative is to design, construct, and evaluate a new VAWT testbed that will allow us to incorporate much of what we have learned about larger vertical-axis turbines since the 17-m machine was built in the late 1970s.

The next obvious scale-up size for research purposes is a 34-m-diameter VAWT that is 50 m high with a center shaft 3 m in diameter; it is rated at 500 kW (Figure 6). Turbines of this size should be more economical because of improved aerodynamic performance and because operating and maintenance costs remain essentially constant while power output increases. In addition, the turbine will have a variable-speed feature, enabling it to operate at maximum efficiency over a fairly broad range of wind speeds (Box B Figure B-1).

Another important part of our evaluation program is to understand stress levels under a variety of operating and control strategies so that we can effectively lengthen machine fatigue life without unduly sacrificing energy capture.

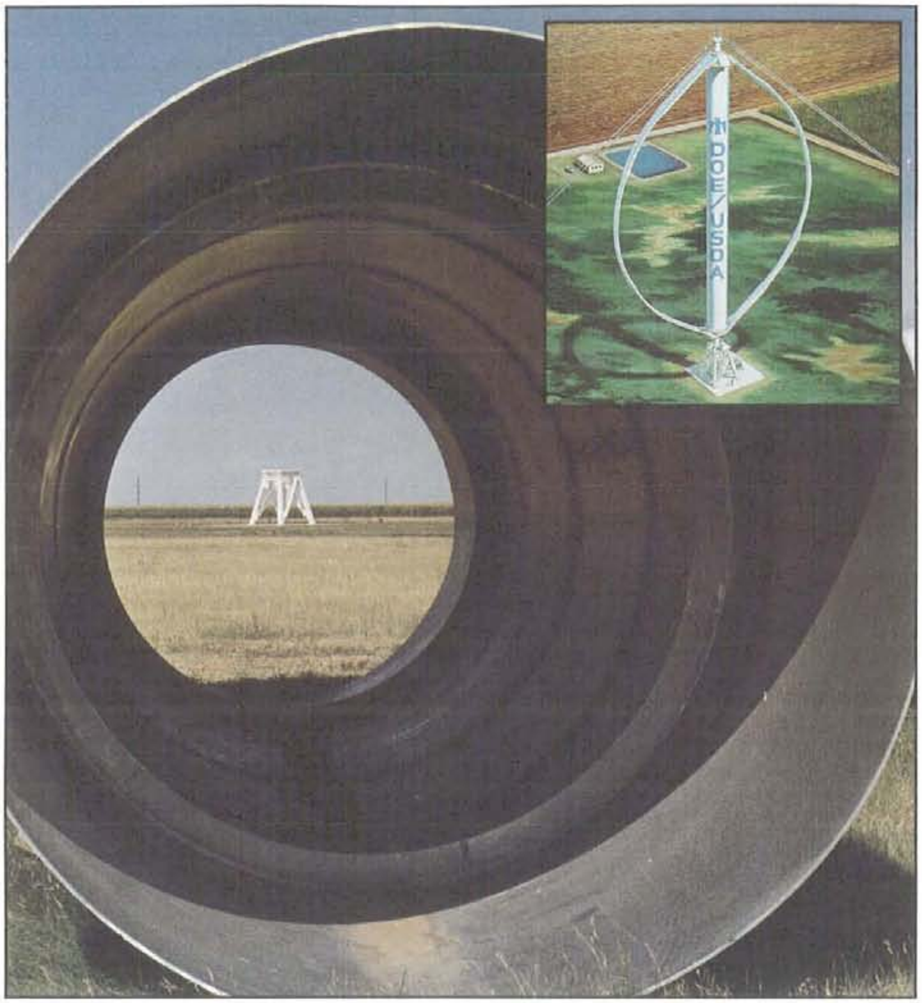


Figure 6
Artist's concept and early construction view of the new 500-kW VAWT research test bed at its evaluation site in west Texas.

Our research is supporting a technology that is commercially well established. Over the past few years many "wind farms" have been installed at good wind sites (especially mountain passes) to feed power into local utility grids.

Virtually all wind farms are in California because of favorable tax incentives and because of an existing electric utility grid with a large demand. Altamont Pass near Livermore has more than 5600 operating HAWTs and VAWTs. This and two other farms — one in the Tehachapi Mountains north of Los Angeles and the other in San Gorgonio Pass near Palm Springs — have a total rated capacity of about 1100 MW. Commercial units sell for about $1000 per rated kilowatt, which has made them very competitive with other forms of energy under federal and state tax incentives. Improvements derived from our research should make VAWTs economically competitive even without tax credits.

BOX B

Natural-Laminar-Flow Airfoils

We have been developing airfoils specifically for use as blade elements on VAWTs. Airfoils originally used were designed for aviation applications and were intended to operate over limited ranges of angle-of-attack, at Reynolds numbers generally in excess of 5 million, and with gentle stall characteristics. VAWT blade elements are at Reynolds numbers from a few hundred thousand to 3-4 million, and in many cases have sharp stalling characteristics to provide positive power regulation in high winds (Figure B-1). Airfoils designed to function on natural-laminar-flow (NLF) principles (profile c, Figure B-2) have been shown to perform better in the VAWT environment than conventional aviation-oriented sections (profile a). The NLF sections have contoured surfaces which produce pressure gradients that provide large chordwise extents of low-drag laminar-boundary layers. This improves energy-conversion efficiencies in low and moderate winds, exhibits excellent power regulation in high winds, allows for lower-cost drive-train components, and contributes to increased fatigue life.

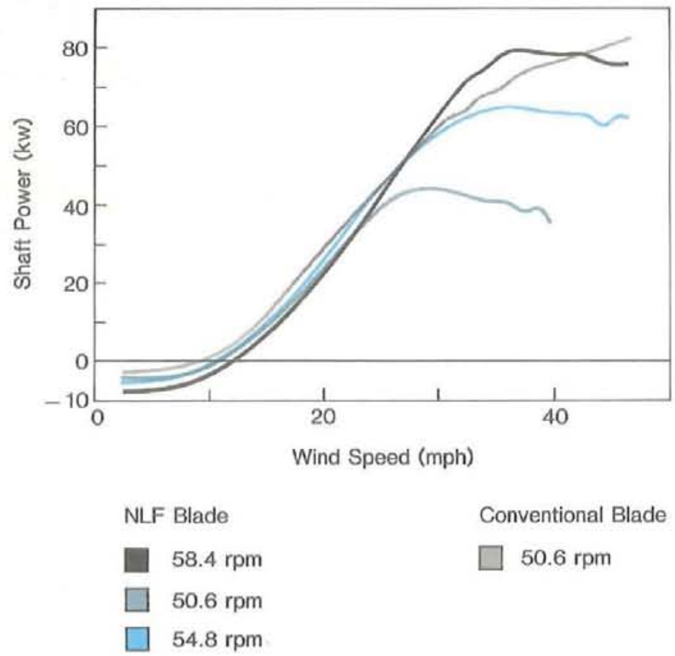


Figure B-1

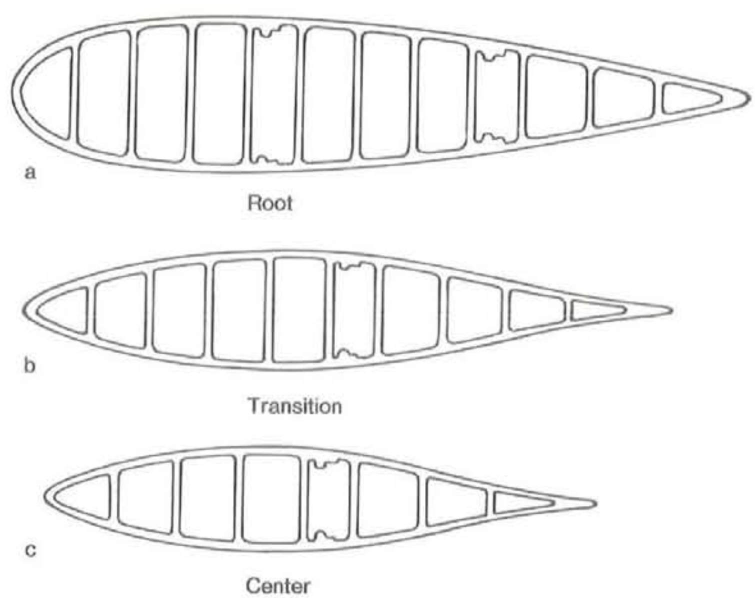


Figure B-2

Solar Energy Potential

An important part of our solar program is the collection and analysis of data from solar-thermal, photovoltaic, and wind systems at field sites around the country. We have learned from this extensive data collection that solar and wind systems do work, but great care must be taken with operational details. If any of these systems are to approach the predicted peak annual energy, they must be kept operating efficiently with a minimum of breakdowns. Although mechanical and electrical failures have been a problem with solar thermal and photovoltaic systems, design improvements based on our extensive test data have significantly improved their performance.

Major achievements in solar technology are

- Solar One, a first-generation solar central receiver thermal plant, is operating successfully and supplying 10 MW of electricity to the local utility grid.
- In our photovoltaics program, we are raising efficiencies in various cell and concentrator technologies. In concentrator photovoltaic technology, we have already demonstrated a cell that converts 28% of the sunlight it receives to electricity and expect shortly to have a working demonstration of a 30%-efficient stacked cell. We are confident that we can continue to take significant steps in improving solar-to-electric conversion efficiencies and solar-cell and concentrator performance.
- The 17-m first-generation VAWTs have been built and tested, and successful commercialization programs have been developed. We are moving on to the next generation of wind-turbine technology and expect to reduce installation, operation, and maintenance costs by as much as a factor of 2.

For more information, call Don Schueler (505) 844-4041.

☆ U.S. GOVERNMENT PRINTING OFFICE 1987—773-109/40017

Index of articles in preceding issues of *Sandia Technology*

Printed in the United States of America
Available from - National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS price codes - Printed copy: A02
Microfiche copy: A01