6/24/77

Doc. 1039

Energy and Technology Review

Lawrence Livermore Laboratory

February 1977

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THE COVER

This photographic montage represents the wide range of research activities carried out at the Laboratory. They illustrate some of the past year's achievements cited by Dr. Roger Batzel in a recent address to staff members on Laboratory accomplishments and trends (see the articles beginning on pp. 1 and 11).

(1) Device canister and support stemming being readied for an underground nuclear test at the Nevada Test Site. (2) Plant bin used in field fumigation experiments in California's Imperial Valley to evaluate the environmental impact of developing the valley's geothermal resources. (3) Core 1 office building, one of four new facilities funded in our proposed FY 1978 budget. (4) Lance missile being fired from its ground carrier; LLL is designing an improved warhead for the missile. (5) Space frame for the 20-arm Shiva laser now being built. (6) Banded structure of kerogen and marlstone in oil shale. For a report on recent advances in our program for recovering oil from oil shale by *in situ* retorting, see the article beginning on p. 19.

ABOUT THE JOURNAL

The Lawrence Livermore Laboratory is operated by the University of California for the United States Energy Research and Development Administration. The Laboratory is one of two nuclear weapons design laboratories in the United States. Today nearly half of our effort is devoted to programs in magnetic and laser fusion energy, biomedical and environmental research, applied energy technology, and other research activities.

The *Energy and Technology Review* is published monthly to report on accomplishments in this energy and environmental research and on unclassified portions of the weapons program. A companion journal, the *Research Monthly*, reports on weapons research and other classified programs. Selected titles from past issues of the *Energy and Technology Review* are listed opposite the inside back cover.

February 1977

Energy and Technology Review

Lawrence Livermore Laboratory

Prepared for **ERDA** under contract No. W-7405-Eng-48

Scientific Editor:

BRIEFS

ii

Robert W. Selden

General Editors:

THE LABORATORY: RETROSPECT AND PROSPECT

1

Richard B. Crawford
Kent L. Cummings
Judyth K. Prono

Dr. Roger Batzel reports on the Laboratory's proposed FY 1978 budget, past achievements, and future priorities.

ACHIEVEMENTS AND DEVELOPMENTS AT LLL

11

The Laboratory's programmatic and research milestones reached in 1976 are summarized.

PROGRESS IN OIL-SHALE RESEARCH

19

Important theoretical and experimental advances are described in our research program directed toward recovering oil from underground oil-shale deposits by in situ methods.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

BRIEFS

The short items on this page announce recent developments of importance. Some of these items may be amplified in future issues; none of this material is reported elsewhere in this issue.

FISSION MEASUREMENTS ON MICROGRAM SAMPLES

The fission cross sections of many of the transplutonic nuclides are important in the production chain of the heavier isotopes like californium-252, since fission removes a link from the chain. Knowledge of these cross sections would also allow us to study the feasibility of burning up reactor actinide wastes by exposure to neutron bombardment. Disposal of these long-lived wastes is a tremendous problem facing the reactor nuclear energy program.

These fission cross sections are poorly known because it's so hard to measure them. The isotopes in question are scarce; it's a major effort to isolate even a few micrograms. But samples that small are almost useless for ordinary fission cross-section measurements.

The powerful new electron linacs that have become available in the last few years have changed this picture. They provide copious quantities of neutrons, emanating in sharp, well-defined pulses from a

concentrated spot, making it feasible to measure neutron energies by time of flight over a short distance. This in turn makes it possible to bring the target isotope sample close to the neutron source, greatly increasing the neutron flux at the sample and reducing the needed sample size.

Using this technique on our 100-MeV electron linac, we have recently completed neutron-induced fission cross-section measurements on a pure 3- μ g sample of curium-245, one of the important links in the californium-252 production chain. Curium-245 is one of the radioactive daughters of berkelium-249. The Savannah River Laboratory extracted it for us from among the other daughters in a specimen of berkelium-249 that had been allowed to decay for a year.

The neutron time-of-flight distance in our experiments was only 3.5 m from the linac target to the curium-245 sample. Our measurements yield new results in the 0.01- to 35-eV neutron energy range. This range is of direct interest for thermal reactor calculations.

LABORATORY TRENDS

The Laboratory: Retrospect and Prospect

Each year the Director of LLL reports to the staff on accomplishments and trends at the Laboratory. The following article summarizes Roger Batzel's address on February 25, 1977, covering such issues as the proposed FY 1978 operating budget, Laboratory trends spanning his tenure as Director since December 1971, and Laboratory priorities in the near future. A second article following this summary highlights some of the specific achievements and developments cited by Dr. Batzel.

Each year I report to the Laboratory staff on the forthcoming year's budget and discuss trends, problems, achievements, and the future. Let me begin with what is of immediate interest to us all. Our proposed FY 1978 operating budget totals \$296 million, representing a 17% increase over FY 1977. Of course, the President's budget is still subject to Congressional and executive review. This new budget will allow us to maintain the overall FY 1977 level of effort in weapons and to substantially expand all other major programs.

Weapons. The President's FY 1978 budget provides for a 10% increase in weapons funding, compared with

the 17% increase in FY 1977. Taking into account inflation and the heavy weaponization workload requiring major hardware expenditures, we realized about a 4% personnel increase in the weapons program this year; these levels will remain about the same for this coming year.

FY 1977 reversed the previous years' downtrend in our weapons work, and FY 1978 will maintain those modest gains. However, increased support is required if we are to have both a healthy advanced development program and the large weaponization effort being proposed for the next five years. Concurrently, a larger effort will be needed to incorporate in these warheads such features as improved handling safety and security against unauthorized use; reduced size, weight, and usage of special nuclear materials; reduced collateral damage; and longer stockpile lifetime.

Energy Programs. The FY 1978 budget provides for dollar increases in all of our major energy programs: laser fusion, advanced laser isotope separation, magnetic fusion energy (MFE), energy and resources, and biomedical and environmental. The corresponding percentage increases will be lower than these dollar

increases because of inflation. The new budget also includes funding for physical (or basic) research, a new budgetary area for the Laboratory. Finally, reimbursables -- tasks we undertake for other government agencies in areas where we have special resources -- will show only a nominal increase in FY 1978. This reflects a policy decision I will discuss later.

Manpower. In terms of manpower at the Laboratory, the new budget will mean the addition of nearly 350 people to our staff. This year we have hired over 1000 new employees -- some 650 new employees added to the staff plus about 400 replacements for our normal turnover. We now number almost 6400. I believe this influx of new people is stimulating to the Laboratory and favorably impacts our ability to carry out programmatic responsibilities.

Equipment and Facilities. The FY 1978 budget provides for an increase in equipment dollars but not as much as we would like. Funding for basic equipment continues to be a problem. The proposed budget for facilities, however, is much more encouraging. Construction funds for four new facilities are included. We have \$12.3 million slated for the Core 1 building (Fig. 1), which will house mainly plant engineering and the technical information department. It is scheduled for occupancy in 1980 by some 350 staff members and will be an important step toward relieving our critical shortage of office space. We are continuing to press for further permanent office, utility, and research space. We believe we are being heard.

The high-explosive flash radiography facility for Site 300 is budgeted for \$10.9 million. It will consist

Fig. 1. Core 1 building. Scheduled for occupancy in February 1980, this 8500-m² office building will house about 350 staff members, mainly from plant engineering and the technical information department. It is a first step toward providing critically needed office space.

of an electron linear accelerator and beam transport system protected in a reinforced concrete building and will be located adjacent to an existing firing bunker at the hydrodynamics test area. This facility is urgently needed to expand our ability to accommodate sophisticated nonnuclear experiments in weapons design.

MFE achievements over the last two years have led to the proposed construction of a \$94 million experimental facility at LLNL, of which \$14 million can be obligated in FY 1978. A successor to our 2XIIIB experiment, this mirror fusion test facility will be the main focus for advancing mirror fusion technology over the next several years.

Finally, the FY 1978 budget includes \$3 million to begin Shiva Nova, an extensive upgrade of the Shiva high-energy laser facility now nearing completion. The goal of Shiva Nova is to demonstrate the scientific feasibility of laser fusion in the early 1980's.

Other new construction at the Laboratory under way or completed this year includes the \$5 million national MFE computer center about to go to bid, the \$5 million rotating target neutron source about 25% completed, and the \$3.7 million plutonium building addition now in service. The building for the \$25 million Shiva laser project has also been completed, and the 20- to 30-TW laser will be operating before the end of the year. One note of interest, the new Visitors Center, which we dedicated last summer as a Bicentennial event, has already had over 9000 people tour its exhibits. Its opening has put us in a much better position to give the public an overview of what we do at the Laboratory.

Laboratory Trends

I think it is useful, from time to time, to review the recent past as a guide for projecting into the future. I would like to turn now to the five-plus years since I became Director on December 1, 1971, and view them in terms of what we know about FY 1978.

The trends in budget and manpower at the Laboratory have been up in all years since FY 1972 except 1974. As you recall, national policy decisions that year severely cut back the U.S. science and technology community, and we suffered a reduction in manpower. You can see in Fig. 2 that our

manpower has increased almost 25% over the five years. You will also note that the distribution of funding over the last five years has changed, reflecting a policy decision to broaden the scope of activities at the Laboratory. Nuclear weapons work has declined from almost 72% in 1972 to some 53% of the budget for this year; in FY 1978, it will account for about half of our funding. The energy programs have all increased their budget shares, as have reimbursables.

Weapons. Despite the declining overall weapons effort, we can point to many accomplishments over the past five years. In December 1971, we had just completed one of our most difficult tasks — weaponization of the Spartan warhead — with the Cannikin test at Amchitka Island. A number of other important developments followed.

Substantial progress was made in developing tactical warheads with reduced side effects (collateral damage). We conducted a number of experiments that expanded our understanding of the physics of thermonuclear explosions. In the accelerated test program — an intensive R&D effort completed last March — we conducted high-yield experiments in anticipation of the Threshold Test Ban Treaty that limits tests to 150 kilotons. This effort produced a number of new high-yield designs for missiles and aircraft, providing the nation with the flexibility to choose among several options for future strategic systems. It also contributed to progress in our weaponization of the B77 bomb for the B-1 bomber and other strategic aircraft.

Completion of the accelerated test effort allowed the weapons program to increase once again its work on tactical systems minimizing collateral damage, like the W79 artillery-fired projectile, and on new strategic designs that conserve special nuclear materials (Fig. 3). An increase in computer capacity over the last five years has also contributed to an increased capability for calculating more complex weapons problems in greater detail.

So, in a period of limited means to undertake more difficult and complex tasks, our weapons leaders have skillfully deployed their resources. The achievements of the program's scientists and engineers have matched Livermore's long tradition of innovation and excellence in the weapons field. [Article continues on p. 6.]

Fig. 2. Comparison of manpower at the Laboratory for FY 1972 and FY 1977, showing the breakdown into major program areas. Over this five-year period, manpower has increased by a quarter and our operating budget has almost doubled. Funding distribution has also changed over the period, reflecting a decision to broaden the scope of Laboratory activities. Energy programs have been substantially expanded, weapons work has declined, in terms of our total effort at LLL.

Fig. 3. The nuclear test program fielded a number of highly sophisticated experiments at the Nevada Test Site during the past year. Here the device canister and support stemming for an underground test are being readied for emplacement. Experiments like this one helped increase our understanding of the physics of nuclear explosions.

Magnetic Fusion. For MFE scientists and engineers, 1972-75 was a period of solving hard problems of plasma confinement, and to that end of developing such new technologies as neutral-beam injection. This work culminated in major successes over the last two years, greatly improving plasma stability, temperature, density, and confinement time. As a result, the mirror concept may now be the most feasible approach for

the future of magnetic fusion. Mirror reactors offer the possibility of power generating facilities on the scale of around a few hundred megawatts. The proposed mirror fusion test facility (Fig. 4) could be the precursor of such a mirror reactor.

Laser Fusion. In 1972, this program was being reorganized and redirected as our laser fusion research began to take on new dimensions and scale. Since then,

Fig. 4. Proposed mirror fusion test facility (MFTF), the next step in scaling up mirror experiments. If approved by Congress, MFTF will be the major mirror research facility operating in the early to mid-1980's. The FY 1978 budget includes \$14 million to begin construction on this experiment, which will be housed in the existing building 431.

Fig. 5. New test-bed facility for laser isotope separation. Now in the final stages of being checked out, this will be a prepilot-plant-level facility.

we have seen a large buildup of staff and resources, accompanied by important research achievements. With Argus, the two-anode, 4-TW laser, irradiated targets have produced a billion neutrons, 100 times more than reported by anyone else. Still larger target yields will be possible with the Shiva laser, which, when completed, will have 20 beams and will deliver 20 to 30 TW of laser energy. The test of its high-power laser components are now being assembled and hung on the Shiva space frame. Initial target irradiations are

scheduled for early next year. I think LLL is now the world leader in laser fusion research.

Laser Isotope Separation. The high cost of conventional uranium enrichment, together with our advanced laser research and some novel concepts, led to our program in laser isotope separation. Early in 1975, we enriched 3 mg of uranium to 3% by two-step laser excitation. Since then, we have been putting together a new LIS test-bed facility (Fig. 5) and are

now in the final stages of checking it out. This will be a preplant-level facility for laser isotope separation.

Energy and Resources. Our energy and resources program began with a broad energy study conducted in 1971-72. The value of this study was recognized, the program was expanded, and a resource planning group was established.

Out of the early study came a number of new concepts for recovering large energy resources. We

received our first funding in this new nonnuclear energy field in FY 1974 under the Plowshare program. As funds have increased, we have progressed in our understanding of such energy technologies as *in situ* coal gasification, *in situ* oil-shale processing, and geothermal resource recovery.

Our 11-day coal gasification experiment at Hoe Creek, Wyoming, this past year was a good first effort, considering that five years ago we had only just come up with the *in situ* concept. This concept has the

Fig. 6. Aerial view of our Imperial Valley geothermal test station near Niland, California. Tests conducted here last year indicated that we can reduce the problem of scale formulation by adding acid to the hot, highly saline brines. Scale control is critical if we are to exploit the Salton Sea's geothermal energy resource.

Fig. 7. Our biomedical and environmental program is studying the environmental impact of developing the Imperial Valley's geothermal resources. ERDA has designated LLL as lead laboratory in a long-term program to assess the valley's environmental quality. Pictured here are plant bins used in field fumigation experiments. Plants are briefly exposed to a gas mixture to be released by geothermal power plants; transpiration and photosynthesis are then monitored.

potential of opening up major resources of deep coal for energy applications. At our geothermal test station near Niland, California (Fig. 6), we have developed methods for counteracting scaling problems caused by the highly saline, hot brines of the Salton Sea. Tests have also shown that high efficiencies can be attained in turbines designed for the LLL "total flow" process of geothermal energy recovery. And in our oil-shale program, we are working with Standard of Indiana and Gulf Oil Company on a proposal to apply *in situ* oil-shale extraction to one of the major oil-shale leases in Colorado. I don't know what the outcome will be, but it is encouraging that we are deeply involved with two major companies interested in pushing this technology.

Along with this work, the Laboratory is involved in a wide spectrum of energy-related activities, including solar ponds, the lithium-water-air battery, composite flywheels, improved combustion techniques, and alternate fuels. Because of our special skills, we have also become involved in nuclear energy problems over the last five years. The narrowing base of uranium resources led ERDA to ask us to lead a hydrogeochemical survey to identify new areas for uranium exploration in the western U.S. We are also involved in such nuclear power problems as nuclear waste management and reactor safeguards.

Bio-Environmental. Our biomedical and environmental program was established in 1963 to

study the environmental consequences of radioactive releases. A growing perception of the biological hazards of fossil fuel effluents, chemicals, and other pollutants has broadened the horizons of this program in the last five years and tripled its budget. The flow cytometer, capable of processing 1000 cells or chromosomes per second, is an example of the advances made in our biomedical work. Such automated analysis systems are needed to identify the biological damage from pollution. Our continuing Imperial Valley project on geothermal energy (Fig. 7) is perhaps the most complete and integrated assessment of the environmental impact of a nonnuclear energy technology in the U.S. ERDA has designated LLL as lead laboratory in this long-term project to evaluate the valley's environmental quality.

Future Priorities

It is clear from the trends over the past five years that the Laboratory has undergone a marked change. Diversification of our interests and effort is here to stay. We have grown with this diversification and will continue to do so. For the future, however, I also see a critical need for expanded weapons work.

Diversification has not reordered the Laboratory's priorities. The nuclear weapons program will continue to be our major responsibility for the foreseeable future. A guiding principle in the choice of new programs must therefore be that they do not interfere with our ability to accomplish weapon program goals.

The present major energy and environmental programs are compatible with, and have enhanced, our weapons research. Because we expect continued growth in these programs, I do not see us undertaking any new, large projects in the near term.

In view of our present program responsibilities, we have also decided to curtail reimbursable work during the next five years. We will continue to conduct reimbursable projects, but with the aim of reducing their level from the current 12% to about 10% in 1980. We still recognize our obligation to do work for the country when we have special skills and resources relating to specific problems.

You have probably heard that the Regents have authorized final preparations for a new contract with ERDA to continue University operation of the Laboratory for another five years, ending in 1982. I am pleased with this development. Our relationship with the University has been mutually beneficial. We are indebted to the Regents, and to the Regents Special Projects Committee that oversees LLL operations, for their advice and help. We are also indebted to President Saxon and his staff for their keen interest in LLL research projects and for their support.

In closing, then, let me say that I believe the pace and quality of R&D progress at LLL are as outstanding as any in the country. Every person on the staff here has contributed — scientists, engineers, technicians, and those in all other support and administrative positions. I would like to congratulate and to thank each of you for helping make this last year one of notable progress.

LABORATORY TRENDS

Achievements and Developments at LLL

In discussing Laboratory trends, Dr. Batzel cited numerous examples of progress recorded during this past year. The following summary highlights some of the programmatic and research milestones that marked 1976 and that represent the diversity of efforts carried out at LLL.

Weapons

The most visible results of the weapons program are nuclear tests and weaponized systems for the stockpile. Underlying these, however, are many projects ranging from basic scientific research up through advanced engineering development. These projects represent the dedicated efforts of people throughout the Laboratory — physicists, chemists, mathematicians, engineers, technicians, secretaries, and many others. The sum of their activities during the past year was considerable progress in areas ranging from warhead weaponization to improvements in safety and the reduction of collateral damage.

The nuclear test program fielded a number of highly sophisticated experiments at the Nevada Test Site during 1976. We are approaching completion of the new 8-in. artillery-fired atomic projectile, the W79. Testing should be completed over the next year to year and a half. Weaponization also continued on a new bomb with supersonic laydown capability for the B-1 bomber, the B77, and on a new warhead for the Lance tactical missile system, the W70 Mod 3 (Fig. 1).

Although tactical weapons activities were curtailed by the accelerated test program up through last March, after the Threshold Test Ban we returned to the tactical weapons needed to modernize NATO forces. We were quite successful in developing new designs for tactical weapons that considerably reduce the collateral damage produced by a nuclear explosion. We also made headway toward greater weapon safety by reducing the probability that a warhead's high-explosive component would detonate accidentally. Toward the same end, we continued work on a practical scheme for protecting nuclear materials and preventing the dispersal of

radioactive material in any circumstance other than intentional warhead detonation.

Advances were made in nuclear weapons test diagnostics, allowing us to measure nuclear explosion phenomena more accurately. We also improved our codes for predicting the structural behavior of warheads subjected to various stresses. These codes are part of our computational engineering analyses that supplement experiments and reduce costs.

Fig. 1. Lance missile being fired from its ground carrier. Weaponization work continued this past year on our W70 Mod 3 warhead for the Lance tactical missile system.

Magnetic Fusion Energy

We again extended our successful experiments in the 2XII-B mirror device this past year, achieving β as (i.e., plasma pressure/magnetic field pressure) of 1.2 to 1.6, compared with the previous high of 0.5. High β means both efficient use of the magnetic field and enhanced mirror confinement. These experimental results thus increase the chances of a highly efficient field-reversed mirror reactor.

A second reactor concept, based on mirrors in tandem, was also developed and evaluated. A major problem with mirror devices is that they preferentially leak electrons out the ends, leaving a net positive potential in the magnetic well. The tandem idea calls for stopping the ends of a long solenoid with two mirror devices, taking advantage of the positive potentials of the mirror plasmas to create the conditions for a stable burn and power generation in the solenoid. This idea has led to the tandem mirror experiment, which is now beginning construction.

As the next step in scaling up mirror experiments, the mirror fusion test facility was proposed last year and favorably reviewed by ERDA. If approved by Congress, it will be a significantly larger mirror experiment than any conducted to date, standing 12 m tall and having about 10 times the confinement volume of 2XII-B.

Construction on the new rotating target neutron source was started in 1976. It will provide 14-MeV neutron bombardment one-fifth as intense as that expected in proposed fusion reactors, enabling us to study neutron damage to various reactor materials. Construction also began on the high-voltage test stand that will be used to test the 80- and 120-keV neutral beam sources now being developed for mirror and tokamak research.

Lasers

The laser fusion program produced a record one-billion fusion reactions this past year with the Argus laser. Completed in mid-1976, the two laser arms of Argus now deliver 4 TW of beam power to their microsphere targets. Argus will continue to be the world's most powerful laser until Shiva comes on line late this year. Shiva will be a 20-arm laser delivering 20 to 30 TW. The building and massive framework

(Fig. 2) for it are complete; the first laser components are now being installed on the framework. We have also begun a preliminary design of Shiva Nova, an upgraded Shiva laser that we expect will take us to scientific breakeven (fusion energy produced equals light energy in the laser pulse) by 1981.

Our understanding of laser fusion has greatly increased over the past year as a result of several hundred experiments on the 0.4-TW Janus, 1-TW Cyclops, and 4-TW Argus lasers. Our LASNEX computer code, which simulates laser-driven implosions, has evolved with this understanding. The code continues to accurately predict experimental results, allowing us to improve target designs.

In our other major research effort — laser isotope separation — we completed a new test-bed facility and continued research in spectroscopy and laser development.

Energy and Resources

Our first field test of *in situ* coal gasification continued for 11 days this past October at Hoe Creek, Wyoming (Fig. 3). An estimated 116 tonnes of coal were gasified, producing 530 000 m³ (19 million scf) of gas with a heating value of 4.1 to 5.6 MJ/m³ (110 to 150 Btu/ft³). These numbers agreed with theoretical predictions.

In our geothermal project, laboratory tests demonstrated that high efficiencies are attainable with an impulse turbine designed for our "total flow" process. Field tests at our Salton Sea test station showed that adding acid to the area's highly saline hot brines drastically reduces scale formulation, a major problem in utilizing the geothermal resources of California's Imperial Valley. Together, these test results indicate that complete brine-tolerant systems based on our total flow concept are realizable.

Oil-shale experiments continued in our small retort (0.3-m diam, 1.5 m high) this past year. Construction was also completed on a larger retort (0.9-m diam, 9 m high), and the first engineering tests were successfully run on it. Experiments with both retorts are being used in planning commercial-scale field tests of our rubble *in situ* extraction concept. Complementing this experimental work, we completed a computer model

to simulate retort reactions and are updating it as new data become available.

For ERDA's National Uranium Resource Evaluation program, we developed several new automated trace-element analysis systems and began hydrogeochemical and stream sediment surveys in Nevada and Utah. We will ultimately oversee surveys of five other western states in this effort to assist private industry by identifying uranium-rich areas favorable for exploration.

Our shallow solar ponds being tested at the Sohio uranium mining and milling plant near Grants, New Mexico, have performed close to prediction, collecting on an annual average about 10 MJ/m² (1000 Btu/ft²) daily. Experiments to improve collection efficiency also continued at LLL (Fig. 4). In another experiment to tap solar energy, we have made encouraging progress with a reactive sputtering technique for making cadmium sulfide solar cells.

Progress was also made in our wind power and gas stimulation studies. Wind-energy-rich subregions on Oahu were identified by numerical simulation and confirmed by measurements. Our theoretical modeling of gas stimulation in tight gas reservoirs by massive hydraulic fracturing has shown promise for answering some of the critical questions of fracture geometry. This modeling work will aid in designing and interpreting future stimulation projects.

Finally, in energy planning we

- Published a major study on the national economic payoff of accelerating research and development for both energy conservation and production.
- Assessed the potential of producing hydrogen and methane from algae.
- Evaluated worldwide petroleum reserves.
- Examined energy storage systems for transportation applications and assessed the potential of a battery-flywheel hybrid vehicle for urban driving.

Biomedical and Environmental

In our biomedical research, we have advanced our understanding of mutagenesis, carcinogenesis, and reproductive effects in a number of ways. For example, we developed and validated a battery of cell-culture

Fig. 2. Space frame for the 20-arm Shiva laser. The first laser components are now being hung on this 270-tonne steel framework. When completed, Shiva will deliver 20 to 30 TW of beam power to ignite thermonuclear reactions in microsphere targets.

Fig. 3. Drilling rigs at Hoe Creek, Wyoming, site of our first field test of *in situ* coal gasification. During an 11-day experiment this past October, some 116 tonnes of coal were gasified underground here, producing 530 000 m³ of gas.

Fig. 4. Shallow solar pond test module at LLL. Adding the 1.8-m-high, plywood-backed reflector panel pictured here to the pond's north side increased efficiency by a factor of 2 in December, and by about 25% on an annual basis.

tests that allows us to test energy-related pollutants for their mutagenic and carcinogenic potential. A new staining technique used with our laser-based flow systems (Fig. 5) has improved resolution for the high-speed analysis of human chromosomes. With two-parameter flow analysis of stained cervical cell samples, we automated the screening process for detecting uterine cancer. And we showed that the ovarian and testicular germ cells of mice and hamsters are uniquely sensitive to chemical carcinogens.

As part of our environmental studies, we characterized stack emissions from western U.S. coal-fired power plants fitted with various control

devices. Burning coal at high temperatures yields smoke that contains significant amounts of toxic elements, and inhaling these emissions poses a potential health hazard. We found that electrostatic precipitators reduce the potential for fly-ash inhalation more than venturi scrubbers. Transuranic research studies in the Marshall Islands showed that the plutonium dose to man there is higher via ingestion than via inhalation. The Islands are the one area of the world where this is true, because of the natives' diet. Finally, our continuing Imperial Valley project has become perhaps the most far-reaching study of the environmental impact of energy development in the U.S.

Fig. 5. The LLL flow cytometer, which can process 1000 cells or chromosomes per second, is an important tool in our biomedical work. Such automated analysis systems are needed to identify pollutant-based biological damage. An improved staining technique has enabled us to increase resolution for the high-speed analysis of human chromosomes with the cytometer.

General Research and Development

In the area of computational support at the Laboratory, a two-dimensional time-dependent computer code was developed this past year to study nuclear heavy-ion interactions and fission theory. A companion three-dimensional code is under development. An elastic-plastic simulation code specifically programmed for the STAR computers began running production problems involving the propagation of cracks in three dimensions. The STARs also became productive in certain design areas, and we added a fourth CDC 7600 to our computer center. In related work, we developed a mobile, computer-based data-acquisition and control system that has already had wide use in our weapons and

energy programs. A high-speed system, it controls an experiment and receives, analyzes, and displays data in real time.

A number of new measuring techniques were also developed at LLL. For example, we devised a new optical method of measuring the height variations of a surface. With submicrometre accuracy, this method has been used to measure the thickness of thin films and is being refined for very precise surface-finish analysis. We also developed a new technique for measuring the depth distribution of hydrogen isotopes absorbed or implanted near the surface of a material, obtaining a sensitivity of one part per million for tritium in copper. This technique has applications in both fusion reactor research and our nuclear explosives programs. To meet the precision requirements of our

equation-of-state research, we developed self-shorting electrical pins capable of measuring shock-wave arrival times with 300-ps accuracy. With these pins we can now make more accurate measurements of nuclear materials at higher pressures than ever before.

Among the new measurements made this past year were extremely precise neutron capture and fission cross sections. These measurements covered a wide range of materials important to the weapons program, but two measurements also established a new estimate for the age of the universe. The Laboratory's 100-MeV linear accelerator provided the intense source of neutrons needed to measure two neutron capture reactions: the creation of osmium-187 from

osmium-186 and the destruction of osmium-187. These measurements enabled us to calibrate the decay of rhenium-187 to osmium-187 as a new astrophysical clock. Our results placed the universe's age at 20 billion years, 6 billion years older than the age determined by other nuclear techniques.

In the areas of materials fabrication and engineering research, we developed a method of bonding uranium to steel that has important applications in the weapons program. We also synthesized a series of new polyurethane adhesives that meet all current weaponization requirements. Our precision engineering research enabled us to diamond turn an x-ray telescope (Fig. 6) that was later shot some 320 km into space

Fig. 6. Diamond-turned x-ray telescope made for the Astronomy Department at the University of California, Berkeley. The telescope was later sent 320 km into space to detect ultraviolet radiation from dying stars.

to detect ultraviolet radiation from dying stars and other stellar phenomena. We also developed a new ion cyclotron mass spectrometer and are evaluating its potential for precise hydrogen-isotope analysis.

Reimbursables

We were named by the FAA as the U.S. Satellite Ozone Analysis Center for monitoring long-term trends and variability in global ozone data provided by a new series of Air Force satellites. Correlated with ground observations, these data will help us establish the current average ozone level and determine how atmospheric pollution affects that level. In related FAA work, we continued our studies of the environmental effects of stratospheric flight for the High-Altitude Pollution Program. This work included numerical modeling of the atmospheric response to airplane effluents.

For the Nuclear Regulatory Commission, we applied instrumentation and experimental techniques developed in our nuclear weapons work to investigate nuclear reactor safety questions. We also began a study of nuclear fuel-cycle waste materials, examining such issues as their classification, solidification, transport, and isolation (permanent storage).

Finally, in nonnuclear weapons-related work this past year, we made significant advances in high-energy propellant studies for the Trident submarine missile program. These advances stemmed from improvements made in our computational capabilities with high-explosive initiation. We also designed and successfully tested a fuze system that can withstand 490 km s^{-2} (50 000 g). This was a requirement for the hard structure munition we developed for the Air Force and has additional applications in both conventional and nuclear ordnance.

FOSSIL ENERGY

Progress Research

Oil shale today appears to offer the best chance of providing substantial quantities of synthetic fuels at competitive prices. Oil-shale deposits in Colorado, Utah, and Wyoming contain more oil than Middle East petroleum reserves. The Piceance Basin in western Colorado contains the bulk of these oil-shale resources that are economically recoverable, of which 350 billion barrels are thought to be exploitable with LLL's rubble *in situ* extraction (RISE) method. Like other modified *in situ* processes, RISE calls for breaking up the shale by mining methods and heating it underground to free the oil. Modified *in situ* extraction now appears to be the prime contender for commercial exploitation, with an excellent chance for large-scale field testing.

Contact Albert J. Rothman (Ext. 8801) for further information on this article.

Although more research and development are clearly needed, we have made advances toward realizing the RISE concept since our last report.¹ This article summarizes important theoretical and experimental results to date.

Oil shale (above) is a dense, impermeable marlstone; its organic content (dr bands) is in the form of kerogen, a solid that must be heated to about 400°C before it breaks down into a petroleumlike liquid. Because neither the liquid nor hot gases can flow through solid rock, the first step in extracting oil from shale is to break the rock up into rubble to make flow passages.

Some small deposits of shale are so rich in kerogen and so near the surface that it may be economical to mine the rock and extract the oil above ground in large steel retorts. This approach is clearly out of the

question for the thick deposits of western Colorado's Piceance Basin, which lie 150 m or more below the surface and yield a moderate 90 or so litres of oil per tonne. By retorting underground, we expect to operate at lower cost, producing oil at an estimated \$8 to \$12/bbl.

Figure 1 illustrates the RISE concept. As can be seen in the block under development, one

simultaneously removes about 20% of the shale to make room and rubblelizes the rest with conventional explosives. In the block being retorted, we see a flame front moving down through the rubble bed, fed by air forced in from above that drives the shale oil and combustion gases before it. The shale oil is pumped away as it accumulates at the bottom of the retorting bed. When the flame front reaches the bottom of the

Fig. 1. Conceptual view of rubble *in situ* extraction (RISE) oil-shale retorting. The various process stages are illustrated in adjacent blocks. In the block under development, about 20% of the shale is being removed by conventional mining techniques to provide void space in the formation, while the remaining shale is progressively broken up into rubble by blasting. In the block being retorted, a flame front burns downward, releasing oil from the shale. Air (or other process gas) fed from above supports combustion and sweeps the oil vapors away from the reaction zone. The spent shale remains in place, supporting the overburden and minimizing subsidence. The oil is pumped away as it arrives at the bottom of the bed. In addition to nitrogen and carbon dioxide, the exhaust contains combustible gases such as carbon monoxide, hydrogen, and other hydrocarbons that may have value as fuel.

bed, the process is repeated in an adjacent block. The spent shale stays in place, supporting the roof of the cavity and minimizing subsidence. Environmental impact is minimal; only minor drilling operations disturb the ground surface, and most of the shale never leaves the ground.

Although modified *in situ* shale oil extraction rests on a base of some retorting experience and conventional mining techniques, a number of questions still need to be answered before anyone would attempt such a large-scale operation. Some of these questions are:

- What is the best process gas? Should it be air, air plus steam, preheated inert gas, or some other mixture?

- What is the best particle size for the rubble bed? Large particles may give poorer oil yields; too many fines could mean too much resistance to gas flow and increased pumping costs. Obviously it is easier to break a huge block of shale into a few large boulders than into many small pebbles. How far must we go in this direction to obtain economic yields of oil?

- How can the exhaust gas be used most effectively to produce byproduct power?

- To what extent will the rubble bed lose permeability or plug up during retorting, and how can we make sure the passages stay clear?

- Can we develop an accurate enough retort model to predict the effects of operating conditions on such factors as temperatures, yields, and gas composition?

Ultimately these questions will have to be addressed in the field. However, field tests are slow and expensive. Laboratory tests and modeling should at least give us a fair start, vastly improving the chances of success in field trials and avoiding expensive false starts and direction shifts.

We have been attacking these problems on theoretical and experimental levels. Among our theoretical projects are the development of a computer model of the retorting process, and investigation of the pressure variation with depth in a rubble-filled retort, both before and during retorting. Experimental projects include investigations of the chemistry of metal carbonate reactions in oil shale and of the reactivity of oil-shale char with oxygen and carbon dioxide, comparison of retort operation with the

theoretical model, and a series of studies to determine the effects of various process parameters — particle size, heating rate, gas flow rate and composition — on oil yield. Recovery rates of 90 to 99% of theoretical were reported for some retort runs.

Modeling Studies

Two areas in which we have made recent progress are modeling the retorting process and calculating the vertical pressure distribution in the rubble bed. Our one-dimensional model simulates the chemico-physical processes in the retort, numerically solving the equations governing bulk gas flow, conductive and convective heat transport, heat transfer between gas stream and shale particles, decomposition of kerogen and carbonate minerals, reaction of carbon with CO_2 and O_2 , and combustion reactions in the gas stream. The model follows, as a function of time and location in the retort, the concentrations of six chemical species in the gas phase and six solid components in each of the different shale particle sizes, and the temperatures of the gas and the shale particles.

We can now model a variety of operating conditions, injecting any desired combination of air, recycled gas, oxygen, and inert gas over a wide range of temperatures and flow rates. In addition, the model handles beds of mixed particle size, separating the size distribution into a few size classes and solving the governing retort equations simultaneously for all classes.

For now we are comparing the retort model calculations with experimental retort data. We have reasonable agreement for reaction-zone propagation rates, stack gas compositions, and thermal profiles in our most recent runs. We will keep making comparisons to uncover and correct weaknesses in the model and to extend its applicability.

Eventually we expect the model to predict *in situ* retorting results and to set up the design criteria for a full-scale RISE retort. Figure 2 illustrates preliminary predictions for retorting in 110-litre/tonne shale containing 30 wt% dolomite and 13 wt% calcite, broken into equal masses of particles 6 and 60 cm in diameter to simulate the broad size distribution expected in practice. The void space in the rubble is 20%.

Fig. 2. Theoretical temperature profiles in an *in situ* retort 25 days after the start of a burn, when temperatures and gas compositions have settled down to a steady state. The solid curves are for particles 60 cm in diameter; the broken curves are for smaller particles 6 cm in diameter. The broad wave is for a burn fed with air, the narrow wave is for one in which half the air is replaced with recycled product gas. Note that in the 100% air case, the burn front has moved to a greater depth, and thus oil production has occurred at a much higher rate.

The calculated thermal profiles in Fig. 2 are for an elapsed time of 25 days, when most of the calculated quantities (except for the widths of the thermal waves) have reached steady values. For a given gas flow rate, the burn fed with air has a faster temperature rise, a higher peak, and a broader wave, and it moves down the rubble bed much faster than the burn in which half of the supplied gas is recycled from the retort outlet.

In a separate study, we modified the theory of pressure in storage silos to calculate the vertical pressure distribution in the rubble bed. Rubble

particles are rough and hard; they can lock together under pressure to bridge across the bed, carrying some of the vertical load to the side walls. Hence the pressure should approach a constant value (1.66 MPa for 104-litre/tonne oil shale in a rubble column 46 m square at ambient temperature) regardless of the depth of rubble or overburden.

At high temperatures, however, oil seeps from the shale and lubricates all the surfaces. If this should cause slippage, it could shift the load from the walls and increase the effective loads deeper in the retort, causing excessive deformation of the hot shale. If this process

went far enough, it might conceivably close some of the void spaces between the particles, restricting air flow.

Retorted shale particles appear just as rough as the unretorted shale — although they are weaker — and there is no oil left in them to lubricate the surfaces. They should be able to support the overburden above the burn front independent of what happens during retorting. It is important to learn how much support they can provide, however, since this affects how thick a shale bed can be retorted.

To find out, we have set up a computer program that takes into account the variations of frictional properties and density with depth, temperature, and composition. The data on how friction depends on these factors are scanty, and we have begun to measure these properties to improve our model. Meanwhile, we have run parametric studies showing how the stress distribution may change during retorting. Also, we hope to expand our model to include the effects of particle crushing on rubble pressure and on loss of porosity and permeability.

Experimental Studies

Shale oil generation from kerogen decomposition involves complex chemical processes and is influenced by a variety of physical and chemical factors. If we are to model the retorting process adequately, we must be able to represent the interplay among these factors.

Our approach has been to simplify the processes as though a single reaction is taking place, and then to determine the reaction's chemical kinetic parameters, i.e., activation energy and frequency factor. Ideally these would be measured from a series of isothermal experiments; by measuring the formation rates of the products from the reactants at a series of constant temperatures, one can learn the reaction order and both the activation energy and the frequency factor governing that reaction. In practice, however, it is impossible to heat a shale sample instantly to a constant temperature. Hence some reaction takes place while the sample is being heated to the isothermal temperature, and the results must be corrected for this effect.

To avoid this problem we had to resort to nonisothermal experiments, where the temperature rises at a uniform rate. This method has the advantage, however, of more closely simulating the conditions in an *in situ* retort.

We have performed both isothermal and nonisothermal determinations on 92-litre/tonne oil shale. Table 1 presents the results. The agreement is very good considering the differences in procedure. Our data also support the assumption of a first-order decomposition mechanism and yield an "effective" kinetics of oil generation that is useful in modeling this complex chemical process.

The shale in an *in situ* retort may be exposed to a wide range of heating rates, depending on our choice

Table 1. Calculated activation energies and frequency factors for first-order decomposition of kerogen into shale oil.

Kinetic parameter ^a	Isothermal	Determination method	
		Nonisothermal	
		Powder	2.5-cm cores
Activation energy, E, kcal/mole	54.0	52.4	53.0
Frequency factor, A, 10 ¹³ s ⁻¹	7.5	2.81	3.17
Log A	13.88	13.45	13.50

^aBased on the Arrhenius equation, $k = A \exp(-E/RT)$.

Fig. 3. Observed oil evolution vs surface temperature for large blocks (18-cm diam and 18 cm long) exposed to temperatures rising constantly at 2, 6, 18, and 60°C/hr. Note the improved oil yield at higher heating rates.

of operating conditions. Published experimental information on the effect of shale's thermal history on oil production is of little use to us; most of it deals with conditions too remote from *in situ* conditions to allow meaningful comparison. This means that we had to make our own measurements, exposing powdered shale and various blocks up to 18 cm in diameter to a heating schedule consisting of a straight linear temperature rise from room temperature to the completion of oil generation at heating rates of 0.75 to 720°C/hr.

We found that the oil yield varied directly with the rate of temperature rise (see Fig. 3). For powdered shale, the best yields — approaching 100% — were obtained with the fastest temperature rises or with an inert gas sweep. The highest sweep rates were best, and these were in the lower range of those we expect for actual *in situ* retorting.

Perhaps the most intriguing result of our work is the finding that, at least up to an 18-cm diameter, particle size makes very little difference in the yield.

Figure 4 gives yield-vs-heating rate curves for powdered shale and for solid blocks 18 cm in diameter and 18 cm long. The differences between the two curves are trivial. We are now experimenting with a 50-cm block to see if this relation still holds.

Another finding is that the rapid gas and vapor evolution that accompanies fast heating is an important factor in improving the yield. Slow heating allows the oil to leave the shale slowly, and some degrades into noncondensable gases and char. Rapid internal gas generation moves the oil quickly to cooler regions, where it can escape being degraded.

Figure 5 shows our new large pilot retort. It is 0.9 m in diameter, stands 9 m tall, and holds 6 tonnes of shale, almost 50 times as much as our smaller retort. We have completed an engineering test run on the large retort, and it is ready for more detailed experimental runs. All of the yield results reported here came from small-retort runs.

An early run on the small retort with inert gas gave a yield of only 78%. This poor showing could have

been caused either by oil degradation or by oil mist escaping up the flue. To check this point, we upgraded the oil collection system. A repeat run under the same operating conditions yielded 99% of assay. This excellent recovery indicates that oil degradation, one of our early concerns, doesn't happen in short sections like our experimental retort. It also indicates the importance of effective oil recovery in avoiding misleading distortion of our yield data.

Oil shale is a poor conductor of heat, and an *in situ* retort will be very large, so heat losses sideways to the walls will be small. This is the justification for using a one-dimensional computer model: the heat flow will be essentially one dimensional. This means that, to properly simulate *in situ* conditions in the experimental retort (and to enable us to compare the computer model with the experimental runs), the heat flow there must be one dimensional, too.

To satisfy this condition, we equipped our retorts with an array of heaters along the walls. Sensors measure the temperature profile along the centerline

of the retort, and our retort computer system sets the power levels on the heaters accordingly. Runs with this heater control demonstrated an almost 20% improvement in yield when compared to those without.

In addition to process control, this same computer system gathers, records, and displays data. Integrating digital voltmeters provide as many as 310 channels of thermocouple input and 90 channels of voltage input for monitoring pressure, flow, humidity, weight, heat flux, and other parameters. The data are recorded on magnetic tape for further processing on the large computer system, e.g., plotting and comparing them with model predictions.

An online gas chromatograph provides valuable insights into the retorting process. Figure 6 shows representative gas analyses for a run on small-particle shale (1- to 2.5-cm diam) with an air-nitrogen mixture as the process gas. Each of the product gases (CO_2 , CO , H_2 , and CH_4) reached its steady state concentration at a different temperature and distance downstream. No CH_4 appeared until about 4 cm after the oxygen was all used up, and the oil appeared even farther downstream. In this run, therefore, the oxygen had no chance to burn any of the oil. The oil curve was calculated from the known kinematics of oil generation with temperature, as mentioned above.

Figure 6 also contains evidence of CO and CO_2 evolution at unexpectedly low temperatures. Both continue to increase in concentration after all the O_2 is gone. Hence the CO_2 must be coming from decomposition of the carbonates in the shale and reacting with the carbon in the char to form CO . These reactions are discussed in more detail below.

Shale decomposition reactions are important to the retorting process: they absorb energy that might be used to release more oil, but they also may help to control the peak temperature. Any complete model of the retorting process must include the chemistry of these reactions.

The shale most typical of anticipated *in situ* field conditions is rich in dolomite and calcite with only minor amounts of other carbonates. Pure dolomite [$\text{CaMg}(\text{CO}_3)_2$] decomposes into magnesium oxide, calcite, and CO_2 . Pure calcite [$\text{Ca}(\text{CO}_3)$] decomposes into calcium oxide and CO_2 .

Fig. 4. Oil yield vs heating rate (logarithmic scale) for powders and for 18-cm blocks of shale. These results show that the yield is affected significantly by heating rate and hardly at all by particle size over this size range.

Fig. 5. New 6-tonne-capacity pilot retort. The flare against the night sky above the framework is burning off product gases from an experimental run.

Fig. 6. Chromatographic analyses of process and product gases in and around the reaction zone in an experimental retort. Nitrogen data are not plotted, since the amount is constant and the other gases are measured relative to nitrogen. Note that the CO and CO₂ concentrations keep rising after all the oxygen is used up. This indicates that carbonate minerals (mainly calcite and dolomite) are decomposing, and that some of the CO₂ is reacting with the char to make CO. Note also that, for this case of uniform small particles, oil, methane (CH₄), and most of the H₂ appear in the gas stream only below where the oxygen vanishes.

Oil shale, unfortunately, is not pure anything. The carbonates can undergo numerous side reactions with the ubiquitous silicate minerals in the shale. We are currently involved in detailed x-ray and thermal-analysis experiments, trying to determine the products, thermodynamics, and kinetics of this important set of reactions. We have identified a reaction between calcite and silica minerals that expedites the release of CO₂ from the calcite. This reaction occurs because the normal thermal decomposition of calcite is inhibited by the partial pressure of CO₂ in the retort; the temperature at which calcite decomposes is quite sensitive to the CO₂ partial pressure.

Of equal importance for analyzing and modeling retort behavior are the reactions of oxygen and carbon

dioxide with the char residue. The former is important because it provides most of the energy for the retorting process; the latter produces CO, one of the prominent combustible constituents in the product gas.

To study these reactions, we retorted individual large cylindrical chunks of shale in an electric oven with various controlled atmospheres. In several cases we excluded oxygen, retorting in pure nitrogen and raising the temperature high enough to liberate CO₂ by carbonate decomposition (700°C). In others we admitted air and nitrogen, and kept the temperature low enough to prevent carbonate decomposition (520°C). In a third group of experiments, we admitted air and nitrogen, and heated to 700°C. After retorting for an appropriate interval, we let the blocks cool and sawed them apart to expose the remaining char.

The first case, with oxygen excluded, permitted only the CO_2 reaction. Light-colored char covered the entire cut face, indicating that the CO_2 -char reaction took place throughout the whole block.

The second case, heating in air and nitrogen below the carbonate decomposition temperature, is illustrated in Fig. 7. The dark char in the center is relatively

mm 0 20 40 60 80 100 120 140
INCH 0 1 2 3 4 5

Fig. 7. Section of a piece of shale that has been retorted in an electric oven in an atmosphere of nitrogen and air at 540°C . A clear line of demarcation appears between the light and dark areas, indicating the depth of oxygen penetration. The hole bored down the axis of the block is a well for thermocouples. Ceramic cement sealed the thermocouples in place and also provided thermal contact with the shale. The red material on the outside is plastic tape wound around to hold the block together while it was being sectioned.

Fig. 8. Permeability vs temperature at two pressures. A vertical pressure of 4 MPa would result from a rubble thickness of about 220 m if there were no support from the sidewalls.

unaffected; around the edges the char is burned away completely. The line of demarcation is sharp, clear, and runs at an almost uniform depth all around the block. The only reaction in this case was that between char and oxygen.

The third case looks almost the same as the block in Fig. 7, except that the char in the middle is somewhat depleted by the CO_2 reaction. Chemical analysis showed that char reacted with both oxygen and carbon dioxide. These experiments enabled us to construct a simple model describing char reactions for incorporation into our retorting model.

We have developed equipment to measure how bed permeability is affected by temperature, bed pressure, oil-shale grade, particle-size distribution, and time. Figure 8 shows some preliminary results. In experiments on 104-litre/tonne oil shale at high

pressures, we observe a slow permeability decrease as the temperature increases to about 300°C. The permeability decreases rapidly between 300 and 400°C, and then becomes constant or increases slightly as the temperature rises further.

Under these conditions, the minimum permeabilities ranged from 0.4 to 10 um^2 (0.4 to 10 Darcy) at pressures of 2 to 6 MPa for samples composed of particles ranging from powder up to 1.2 cm in diameter. These pressures result from rubble columns about 110 to 330 cm high if we ignore sidewall support. We have also observed a trend toward higher permeabilities when the particle diameters ranged from 1.2 to 2.5 cm. We need more data, however, before we can evaluate the relationship between particle-size distribution and permeability, and extrapolate it to cover the particle sizes (ranging up to perhaps 60 cm) anticipated in an *in situ* retort.

Conclusions

The results of these theoretical and experimental studies continue to show promising signs that we are on the right track of a method to utilize our national oil-shale resources. This work also reveals that considerable effort needs to be devoted to understanding the complex processes involved and to finding practical solutions for full-scale *in situ* operations. We are continuing our research and development program for this important national resource.

Notes and References

1. For an explanation of the RISE concept and a report of earlier work, see the June 1975 *Energy and Technology Review* (UCRL-52000-75-6), pp. 6 and 10.

For Further Reading

- A. Braun and A. Rothman, "Oil Shale Pyrolysis: Kinetics and Mechanism of Oil Production," *Fuel* **54**, 129 (1975).
- J. Campbell, G. Koskinas, and N. Stout, *The Kinetics of Decomposition of Colorado Oil Shale: 1. Oil Generation*, Lawrence Livermore Laboratory, Rept. UCRL-52089 (1976).
- J. Carley, *Pressure Distribution in Beds of Oil Shale Rubble*, Lawrence Livermore Laboratory, Rept. UCRL-51957 (1975).
- A. Lewis, "The Outlook for Oil Shale," in *Proceedings American Association for the Advancement of Science Symposium San Francisco, 1974*.
- A. Lewis and A. Rothman, *Rubble In Situ Extraction (RISE): A Proposed Program for Recovery of Oil from Oil Shale*, Lawrence Livermore Laboratory, Rept. UCRL-51768 (1975).
- R. Mallon and R. Braun, "Reactivity of Oil Shale Carbonaceous Residue with Oxygen and Carbon Dioxide," *Quarterly, Colorado School of Mines* **71** (4), 309 (1976).
- R. Mallon and W. Miller, "Thermal Behavior of Oil Shale Blocks Heated in Air," *Quarterly, Colorado School of Mines* **70** (3), 221 (1975).
- J. Raley and R. Braun, "Oil Degradation During Oil Shale Retorting," in *Proceedings Symposium on Oil Shale, Tar Sands, and Related Materials, San Francisco, August 29-September 3, 1976*.
- W. Reynolds, *Mining Considerations for In Situ Oil Shale Development*, Lawrence Livermore Laboratory, Rept. UCRL-51867 (1975).
- A. Rothman, "Research and Development on Rubble In Situ Extraction of Oil Shale (RISE) at Lawrence Livermore Laboratory," *Quarterly, Colorado School of Mines* **70** (3), 159 (1975).
- N. Stout, G. Koskinas, J. Raley, S. Santor, R. Opila, and A. Rothman, "Pyrolysis of Oil Shale: The Effects of Thermal History on Oil Yield," *Quarterly, Colorado School of Mines* **71** (4), 153 (1976).

PAST TITLES

Articles in the *Energy and Technology Review* have been organized into subject areas approximately corresponding to the Assistant Administrators' areas of responsibility in the Energy Research and Development Administration. These subject areas are listed below with references to some recent articles in each category. (A semiannual index appears in the June and December issues.)

Conservation

The Methanol Engine: A Transportation Strategy for the Post-Petroleum Era (*December 1976*)
Flywheel-Battery Hybrid: A New Concept for Vehicle Propulsion (*June 1976*)

Environment and Safety

Phantom Construction: Building a Torso Manikin for Whole-Body Counting (*December 1976*)
Getting the Facts About Ozone (*November 1976*)
Characterizing Stack Emissions from Coal-Fired Power Plants (*October 1976*)
LLL Biomedical and Environmental Research Program Overview (*May 1976*)

Fossil Energy

Hoe Creek No. 1: An *In Situ* Coal Gasification Experiment (*January 1977*)
Underground Coal Gasification in the U.S.S.R. (*September 1976*)
Forecasting the World's Crude Oil Supply (*July 1976*)

National Security

Imaging Implosion Dynamics: The X-Ray Pinhole/Streak Camera (*December 1976*)
Soviet Experience with Peaceful Uses of Nuclear Explosions (*September 1976*)
Electric Gun: A Versatile Tool for Studying Explosive Initiation (*August 1976*)
The Slapper: A New Kind of Detonator (*July 1976*)
LLL Laser Program Overview (*February 1976*)

Nuclear Energy

Safety and Safeguards: Defining the Issues (*October 1976*)
Automated Uranium Assays (*July 1976*)
Laser Excitation Spectroscopy of Uranium (*February 1976*)

Physical Sciences and Engineering

Mapping Underground Structure with Radio Waves (*January 1977*)
DISPLAY: An Interactive Picture Editor (*January 1977*)
Taking the Moon's Internal Temperature (*November 1976*)

Solar, Geothermal, and Advanced Energy Systems

National MFE Computer Center: 1976 Update (*December 1976*)
LLL Magnetic Fusion Energy Program: An Overview (*June 1976*)
Control of Geothermal Scaling and Corrosion (*March 1976*)

NOTICES

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

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
Price: Printed Copy \$4.00; Microfiche \$2.25