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2XIIB
MIRROR
MACHINE

LAWRENCE
LIVERMORE
LABORATORY

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Energy and Technology Review

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ABOUT THE COVER

Looking down into a model of 2XIIB, a mirror machine at LLL. The C-shaped magnetic coils (center) form the magnetic well that confines the fan-shaped target plasma. A burst of hot plasma is injected into the central vacuum chamber from plasma guns (not shown) at the right; this burst is trapped, compressed, and heated by pulsing on the magnetic coils. The target plasma is further heated and sustained by 12 pulsed neutral beams, 6 per side, represented here as the vertical red column. The fast-gate coils at the far right close the magnetic field after plasma injection. Length between the mirrors is 1.5 m. For results of recent experiments on the 2XIIB mirror machine, see the article beginning on p. 1.

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HOE CREEK COAL GASIFICATION EXPERIMENTS UNDER WAY

On November 5, in the Hoe Creek area of Wyoming 32 km south of Gillette, we fired 340 kg of chemical explosives in each of two adjacent holes to fracture an 8-m-thick coal bed at a depth of 46 m. This was the first preparatory step in a program of field testing to explore LLL *in situ* coal gasification technology.

The charges, fired simultaneously in 75-cm-underreamed holes 8 m apart, caused a surface displacement of less than 30 cm. Preliminary level surveying indicates a residual upward displacement of about 6 cm. These results agree well with predictions. Post-shot drilling and instrumentation are now under way, together with site characterization, to determine the extent of fracturing and permeability enhancement. This work will continue for several

weeks to assess several critical parameters: HE performance, integrity of the fractured zone's earth overburden, instrument survivability, and surface, seismic, and pipe motions.

The LLL concept for coal gasification technology — described in last April's *Energy and Technology Review* — calls for chemical explosives to be emplaced in thick, deep coal beds and detonated to create discrete zones of coal rubble. The zones are then ignited, oxygen and steam are pumped in, and the burn front moves through the rubble, producing combustible gases that are in turn pumped to the surface for processing. The ultimate aim is to produce medium-heat-value gas that can be upgraded to pipeline quality from coal resources too deep (150 to 1000 m) for economic recovery by conventional mining methods.

Once our preliminary assessments at Hoe Creek are completed — probably in late December or early January — we will attempt simple (air-only) gasification if fracture-induced permeabilities are adequate. The main objective will be to compare propagation and control of the burn front with our predictions. In particular, we want to know whether the tars and water produced in the combustion process will tend to plug the coal fractures on which permeability depends. We will also look for any adverse environmental effects, such as contamination of aquifers in the coal. We hope that this shallow-depth work will be a cheaper way to anticipate and solve the problems of deep *in situ* coal gasification.

A more complex shallow-gasification effort at the same Hoe Creek site is slated for next year. For these experiments, an array of five HE holes — four each at the corners of a 15-m square plus one in the center — will be drilled to a depth of 60 m. Explosive charges totaling as much as 3.4 tonnes will be divided among the five holes; again, gasification studies will follow fracturing.

Casing being emplaced in the oxygen injection well. Drill rig in background is for the explosive holes.

AES
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ADVANCED ENERGY SYSTEMS! ↗

2XIIIB: HEATING AND CONTAINING MAGNETICALLY CONFINED PLASMAS

Recent experiments on the 2XIIIB mirror machine have produced encouraging results: a buildup of hot ion densities to $4 \times 10^{13} \text{ cm}^{-3}$, ion temperatures of 13 keV (the highest ever observed in a major fusion experiment), and a confinement time exceeding 5 ms. Two major factors in these achievements were the injection of twelve 20-keV neutral beams to increase plasma temperature and the introduction of warm streaming plasma to suppress microinstabilities. With them, near-classical confinement of a hot plasma was demonstrated. We are now doubling the injected neutral beam energy to see if plasma stability and energy scaling of plasma confinement persist at higher ion temperatures.

Since its beginning, plasma research has aimed at achieving the plasma density, temperature, and confinement time needed for fusion. The near-term scientific goal is to obtain the technical knowledge needed to secure a net positive energy release from nuclear fusion reactions. The more distant practical goal is to establish fusion as an economical and environmentally acceptable primary energy source for generating electricity. Experiments in both toroidal and mirror confinement systems have proved that the idea of magnetic confinement is feasible, but they have not yet proved the feasibility of fusion reactors based on that idea. This is because the experiments have been carried out at plasma temperatures and density-confinement time products ($n\tau$) well below those needed for a reactor.

Research in magnetic confinement focused at first on understanding the nature of hot plasma and its instability modes and more recently on discovering how to avoid, or at least tolerably weaken, the effect of these instabilities. The problem of attaining a quiescent plasma in mirror systems has proved difficult. A plasma is a gas of charged particles coupled together by long-range electric forces that can and do result in collective currents and electric fields. If the resulting plasma waves and oscillations are allowed to grow to large amplitudes, the turbulences they produce cause plasma to leak through the mirrors much faster than the classical rate predicted for a quiescent plasma

(i.e., one in which only the normal level of thermal fluctuations exists). To control these microinstabilities, the plasma must be carefully prepared, avoiding conditions where particle velocities are not well randomized. The growth rate of unstable waves can also be limited by adjusting the shape and intensity of the confining magnetic field.

One of the more successful mirror experiments has been the 2XII (two-ex-two) experiment at LLL. In this mirror machine, highly quiescent plasmas at high densities (10^{13} to 10^{14} particles/cm³) and relatively high temperatures (1 to 3 keV) were achieved through careful control of plasma conditions. Along with quiescent plasmas, high beta values were also demonstrated. (Beta is the ratio of internal plasma pressure to maximum external magnetic pressure; high betas imply efficient use of the magnetic fields and are preferred for fusion reactors because fusion power varies as β^2 .) Beta values of 0.5 were achieved with 2XII, in close agreement with theoretical limits. Based on these successes, the experiment was modified (2XIIIB) to reach higher ion energies and provide a means for sustaining the plasma density.

2XIIIB Facility

Table 1 compares the magnetic field characteristics of 2XII and 2XIIIB. The principal new feature of 2XIIIB is a neutral beam injection system consisting of 12 sources. Developed at Lawrence Berkeley Laboratory jointly with LLL, these pulsed sources can inject several hundred amperes equivalent of neutral atoms

Table 1. Magnetic field characteristics of 2XII and 2XIIIB

Parameters	2XII	2XIIIB
Maximum dc guide field, T	0.2	0.3
Maximum central field, T	0.65	0.9
Magnetic field rise time, ms	0.4	0.5
Magnetic field decay time, ms	8	10
Longitudinal mirror ratio	2	2
Distance between mirrors, cm	115	150
Radial well depth at wall, %	21	64
Maximum plasma diameter, cm	30	100
Transverse access at coil, m ²	0.2	1.0

Contact Frederic H. Coengsen (Ext. 7501) for further information on this article.

FUSION POWER: POTENTIAL AND PROGRESS

Fusion power is potentially a safe source of energy based on a universally available and virtually limitless fuel. Deuterium, fusion's primary fuel, is a stable isotope of hydrogen. The supply of deuterium in the world's oceans could sustain present world energy consumption for 100 billion years — 10 times the estimated age of our universe. It also appears likely that fusion reactors will pose a smaller hazard to man and his environment than any other major power source except solar energy. However, fusion is still in a research phase, with many scientific and economic problems to be resolved before fusion reactors can be developed.

To extract power from controlled fusion reactions, we must find practical, economical ways to accomplish three steps: (1) heat a small amount of fusion fuel (plasma) above its ignition temperature, (2) confine this heated plasma long enough for the energy released to exceed the initial heating energy, and (3) convert the released energy into useful forms — electricity and process heat. Another way to define the requirements for net fusion power is through the Lawson criterion. In general, the product of plasma density and the time for plasma energy to leak out of the system must be at least 10^{13} to 10^{14} particles/cm³·s, with an ion temperature greater than 5 keV.

Fusion research has been under way for more than two decades, and major progress has been made. Minimum practical plasma densities were achieved in 1953, minimum ion temperatures in 1962, and adequate confinement time in 1969. However, for a practical fusion energy gain, all three requirements must be met in a single experiment; to date, only combinations of two have been achieved.

One approach to fusion research is magnetic confinement, which calls for containing a very hot, low-density plasma in specially shaped magnetic fields. There are two basic magnetic confinement configurations:

Magnetic mirror

open-ended machines (mirror or theta pinch) and closed toroidal confinement. In a mirror machine, the magnetic field confines the plasma, preventing motion across the field lines (arrows); strengthened fields at the ends (mirrors) repeatedly reflect the particles back and forth, inhibiting particle losses out the ends. Through collisions, however, particles can be deflected to move nearly parallel to the direction of the field lines and escape out the ends; thus mirror machines always have slow leaks. In a torus, the magnetic field is produced by a magnet coil wrapped around the chamber wall as though a long tubular coil were bent into a circle, closing on itself. Field lines become a family of concentric circles lying wholly

inside the chamber. There are no ends for leaking in a torus, but particle diffusion across field lines still occurs and plasma contamination becomes a problem.

Plasma instabilities pose problems for all confinement schemes. By its own motions, plasma can set up self-generated electric or magnetic fields, foiling attempts to confine it by imposed magnetic fields. Hot plasma can exhibit two classes of instabilities: hydromagnetic (MHD) and wave-turbulence. MHD instabilities are the most violent, dumping a plasma in microseconds; they can arise whenever the plasma is given a chance to expand in a direction of weakening magnetic field strength. All early approaches to fusion failed because of such instabilities. The answer, found in the 1960's, is to make the shape of the confining field more complex.

In a mirror machine, it is possible to reshape the confining field so that field intensity increases in every direction away from the machine's geometrical center. This field is called a magnetic well; plasma trapped within it is forced to remain there like a ball resting at the bottom of a hemispherical cup. A second control method, magnetic shear, is similarly useful for toroidal systems. Between magnetic well and shear effects, MHD instabilities can be suppressed, which leaves wave turbulences. It is toward understanding and controlling these residual instabilities that much of the attention in fusion research has now turned.

Torus

into the plasma, increasing the ion temperature. A second major new feature of 2XIIB is a streaming plasma injector that provides a flow of warm plasma along the magnetic field lines. The presence of this moderately dense "background plasma" permeating the mirror confinement region enhances plasma stability.

Figure 1 is a schematic drawing of the 2XIIB facility. Plasma is injected from the deuterated-titanium plasma guns and flows along uniform magnetic field lines generated by currents in the dc magnets. Part of the injected plasma is trapped in the confinement chamber, compressed, and heated by the fields of the gate and compression magnets. The fast-gate magnet traps plasma from the guns. The nested C-shaped coils have two roles: they compress the plasma, increasing its temperature and density, and they form the confining magnetic field. These coils are shaped (yin-yang geometry) to provide MHD plasma

stability by creating a magnetic field that increases in every direction from the confined plasma. The resulting target plasma assumes the shape of two fans intersecting orthogonally. Twelve 20-keV neutral beams furnish an intense flow of high-energy deuterium atoms, which penetrate the confining magnetic field and are ionized by the existing plasma. Once ionized, these atoms are captured within the magnetic well and sustain plasma density while increasing plasma temperature. Figure 2 shows the laboratory setup of 2XIIB.

Five major plasma-parameter goals were initially set for the 2XIIB mirror machine:

- A product of ion density and confinement time, $n\tau$, on the order of 10^{11} particles/cm³·s.
- An ion containment time greater than 10 ms.
- An ion temperature of about 10 keV.
- The square of the ratio of ion plasma frequency to ion cyclotron frequency greater than 100.

Fig. 1. — In 2XIIB, plasma confinement occurs in a vacuum chamber buried inside the magnet coils at the midplane of the machine. The plasma is created by injecting a burst of hot plasma from pulsed plasma guns. This burst is trapped between the mirrors and compression-heated by pulsing on the mirror coils. Twelve neutral beams further heat and sustain the plasma. Plasma that is not initially trapped or escapes the confining magnetic field is adsorbed on the clean titanium surfaces in the end chambers.

● Demonstration of sustaining such a plasma by means of neutral injection.

We also wanted to understand more fully the scaling of $n\tau$ with ion temperature and other parameters, the effects of finite β , and the effects of the ratio of plasma dimensions to the Larmor radius (radius of the spiraling particles in the plasma).

2XIIB Results. In recent experiments on 2XIIB, we have apparently equaled or exceeded all these plasma-parameter goals. By conservative estimate, we have achieved an $n\tau$ product of better than $7.5 \times 10^{10} \text{ cm}^{-3}\cdot\text{s}$. With the injection of streaming plasma to suppress microinstabilities, we have measured a buildup of hot ion densities to $4 \times 10^{13} \text{ cm}^{-3}$ and ion temperatures of 13 keV, the highest ever observed in a major fusion experiment. Confinement time is better than 5 ms and may have been as long as 13 ms; this is substantially better than

that achieved on 2XII. Our results also show that the hotter the plasma, the longer it can be confined by a mirror machine. We now have experimental evidence, spanning ion temperatures from 2 to 10 keV, that, upon stabilization, $n\tau$ increases with energy.

Analysis of Results. We have interpreted the improved confinement of 2XIIB in terms of warm plasma suppressing high-frequency oscillations in the target plasma, markedly reducing anomalous end losses. Table 2 summarizes the characteristics of plasmas formed under varying operating conditions of 2XIIB. Neutral beam injection increases the mean ion energy from several keV to 13 keV in a few hundred microseconds. Thomson scattering electron-temperature measurements indicate that this ion heating also produces electron heating. Without streaming plasma, however, neutral beam injection does not increase particle lifetimes or density buildup. We attribute this

Fig. 2. 2XIIB mirror machine viewed from the top. The plasma guns are located on the upper right diagonal. The two circular tanks house the neutral beam sources.

Table 2. 2XIIB target plasma characteristics

Operating mode	Ion energy, keV	Electron temperature, eV	τ , ms	$n\tau$, $\text{cm}^{-3}\cdot\text{s}$
Target	2-5	80	0.2-0.4	$\sim 10^{10}$
Target + beams	13	200-300	0.2-0.4	$\sim 10^{10}$
Target + stream	2.5-4	—	1.4	2.8×10^{10}
Target + beams + stream	13	—	>5	$>7.5 \times 10^{10}$

behavior to an enhanced level of ion cyclotron noise produced by the beams; in past experiments, such high-frequency activity has always been associated with reduced confinement time.

Introducing a small percentage of lower-energy ions (streaming plasma) reduces the level of ion cyclotron fluctuations; with this lowered level, the neutral beam

input then increases the hot-ion density, as shown in Fig. 3. The agreement between the density, diamagnetic loop, and neutron measurements in this figure, together with other corroborating measurements, indicates that the measured increase represents a buildup of hot (13-keV) plasma rather than cold ion accumulation from the streaming plasma. When the streaming plasma is terminated, a rapid density loss occurs, and ion cyclotron noise again increases.

The warm plasma appears to restrict particle losses to values near those predicted for classical scattering. Without neutral beam injection, if the plasma stream is introduced early during the magnetic compression, the plasma decay after compression is consistent with losses arising from binary collisions. For the duration of the plasma stream, $n\tau$ is a constant, indicating that nonclassical loss mechanisms — i.e., instabilities — have been greatly reduced. During plasma streaming, the mean ion energy remains nearly constant; by contrast, shots without this plasma stream show an increase of mean ion energy due to spreading of the ion energy spectrum by the ion cyclotron fluctuations.

Microwave interferometry measurements of plasma density and its temporal decay rate have been correlated to various injected neutral beam intensities.¹ This correlation enables us to determine a hot plasma volume of six litres and gives an estimated loss time of 13 ms. The range of uncertainty here places a lower limit of 5 ms on τ ; the upper limit is indeterminate. In Fig. 4, this indeterminacy is shown by an arrow on the upper end of the error bar. The solid circles are values of $n\tau$ obtained at mean plasma energies of 4, 7, and 13 keV. The open circles represent a second measurement of the loss time obtained by switching off the neutral beam and measuring the ensuing decay rate of plasma density. To compare these experimental values with predicted energy scaling, we have included a curve whose coefficient is about one-third of that found in Fokker-Planck calculations without the

Fig. 3. Buildup of 2XIIB target plasma with and without the injection of streaming plasma as shown by density, diamagnetic loop, and neutron measurements. The agreement between these measurements indicates that the measured density buildup is of hot (13-keV) plasma and not cold ion accumulation.

Fig. 4. Plasma confinement in 2XIIB as a function of energy, showing the scaling of $n\tau$ with energy. The straight line indicates the best possible confinement performance as predicted by theory.

streaming plasma. The energy dependence of $n\tau$ is close to that predicted. For a more accurate comparison, we are modifying the Fokker-Planck model (the principal computational model for evaluating plasma behavior) to include this plasma stream.

Future Experimental Directions

The recent 2XIIB results, taken together with our interpretation of their plasma stabilization import, suggest that the reactor regime — involving higher temperatures, higher magnetic fields, and larger plasma sizes — should be more favorable to achieving classical confinement than our present experimental facility. Warm plasma stabilization appears to explain both the marked suppression of particle losses observed in 2XIIB and the anomalously stable behavior of earlier mirror experiments. The goal of the LLL magnetic confinement program is to prepare the way for developing mirror fusion reactors; our progress toward stable confinement in 2XIIB makes us optimistic about these reactors. As a class, mirror reactors offer several advantages:

- Compactness: mirror reactors could be relatively small but with high power density and intermediate power output.
- Relative insensitivity to plasma contamination.
- Adaptability to high-efficiency direct conversion.

Fig. 5. Progress in LLL mirror-machine experiments compared with projected mirror reactor regimes; solid circles represent experimental data, open circles are projections.

We are now altering the 2XIIB facility — doubling (to 40 keV) the injected neutral beam energy — to investigate plasma stability at temperatures up to 30 keV. Our encouraging results to date raise the possibility that a next-generation experiment (MX) could demonstrate the feasibility of mirror reactors (see Fig. 5). The 2XIIB mirror machine approaches reactor temperatures and densities but lacks the necessary confinement time (about 1 s for mirror reactors). However, the use of a superconducting magnet in Baseball II (BBII), a companion mirror experiment at LLL, has produced longer confinement times, though with a low-density plasma. A next-generation experiment combining the technologies of both facilities could be in operation in the early 1980's.

Key Words: magnetic mirrors; mirror machines; neutral particle beams — injection; plasma waves — stability; plasma waves — turbulence; plasmas — heating; streaming plasma; thermonuclear reactors; Two-X; 2XIIB machine.

LASERS AND LASER APPLICATIONS

E/
NSA; ERA

NARROWBAND FLUORESCER USED TO DRIVE AN IODINE PHOTODISSOCIATION LASER

The high energy and average power eventually required for a laser-fusion power reactor preclude the use of solid-state or liquid lasers as now conceived. A program is under way at LLL to develop short-wavelength, high-efficiency, gas-laser media that have the appropriate physical characteristics for reactor applications. Photolytic lasers pumped by narrowband excimer fluorescence are one possibility. We recently demonstrated an iodine photodissociation laser using fluorescence from the XeBr* excimer as a pump source. We are pursuing this scheme as a candidate source for future laser-research facilities.

The development of efficient, high-power new lasers is one of the most important problems bearing on the ultimate use of laser-driven fusion reactions as an energy source. The lasers required to drive the fusion core of an eventual 1-GW pilot plant will have to meet some truly severe specifications: high peak power per pulse (>100 TW), high average power (pulse rates of

~ 100 Hz), and high overall efficiency ($>10\%$ for pure fusion reactors, $>3\%$ for fusion-fission hybrids). Although the elements of a program designed to get us into this parameter space are not yet fully defined, these specifications appear to limit the types of laser media one should study to the following:

- Metastable species where energy is channeled to the excited upper laser level and is stored there until extracted.
- Gases, which can be exchanged between shots (unlike solid-state media) and which minimize flow effects on the optical field (unlike liquid media).
- Simple spectroscopic structure to simplify energy channeling and extraction; this implies atoms or simple molecules.

In addition, account must be taken of wavelength effects in the absorption of laser light at the target. A long-wavelength laser transition may require the construction of expensive targets to facilitate useful absorption of the laser light. Thus attention has centered on short-wavelength transitions involving electronic levels of atoms or molecules. We have a

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LLL LASER PROGRAM

This Laboratory is conducting a program to assess the scientific feasibility of laser-driven implosion and thermonuclear burn of microscopic targets containing deuterium and tritium. Experiments are being run on a single-shot basis, the emphasis being on fast diagnostics of neutron, x-ray, α -particle, and scattered laser-light fluxes from the target. Our laser source for this work is the Nd:glass laser operating in a master oscillator-power amplifier configuration, where a well-characterized, mode-locked pulse is shaped and amplified by successive stages to peak powers of a few terawatts in a 20-cm-diam beam.

A series of Nd:glass laser systems is planned, scaling from the 0.4-TW Janus system operational today to a 100- to 200-TW system proposed in the early 1980's. A key stage in these scaleup experiments is targeted for FY 1978, when 20 TW of peak laser power will be delivered to a target from 20 separate output stages by SHIVA, the Laboratory's \$25 million target-irradiation facility. Experiments with SHIVA are expected to demonstrate significant thermonuclear burn by laser-driven implosion of the target.

Beyond these basic questions of scientific feasibility lie the difficult issues of the technical feasibility and cost-effectiveness of lasers for commercial applications. As explained in the accompanying article, the lasers for future power reactors will clearly be gas lasers.

One of the most convenient ways to excite large volumes of gas is by injecting relativistic electron beams. The resulting secondary electron gas produces the desired excited species through collisional processes. Two approaches have been followed in applying this concept: direct bombardment of the laser gas by electrons, and bombardment of a fluorescer gas that in turn excites the laser gas in an adjacent container with light (a photolytic or optically pumped system). Both techniques are being explored experimentally at LLL.

program in progress at LLL to develop photolytically driven laser systems appropriate for reactors.

Photolytic Lasers. The photodissociation iodine laser is one of the leading candidates for laser-fusion applications. It uses the photodissociation of alkyl iodides, usually CF_3I or $\text{C}_3\text{F}_7\text{I}$, to generate excited iodine atoms. The long radiative lifetime of I^* (130 ms) gives this laser an attractive potential for high power output. The energy storage characteristics and kinetic processes of iodine lasers have been studied extensively,² and substantial system scaling on a single-shot basis is being attempted at the Max-Planck-Institut für Plasmaphysik in Germany. However, the efficiency of these lasers has been limited by poor coupling between the emission spectrum of the xenon flashlamps used and the absorption spectra of the alkyl iodides. Recent experiments with arc sources driven at current densities of about 80 kA/cm^2 have yielded at most a 3 to 4% transfer of input energy into radiation suitable for exciting the alkyl iodides.³ Moreover, the use of xenon flashlamps for scaling to high average powers (multiple pulses) is highly questionable.

For more efficient optical pumping (excitation) of the iodides, and for potential scaling to high average powers, an intense light in the ultraviolet region is needed. A recently discovered new class of narrowband fluorescers — rare-gas halides — provides just such an intense series of near-uv photolysis sources.⁴ The fluorescence is produced by the decay of excimer states of these halides.⁵ As shown in Fig. 6, the band emitted by the XeBr^* molecule shows significant coupling to the absorption spectrum of $\text{C}_3\text{F}_7\text{I}$.

Electron-Beam-Driven Photolysis. In a recent experiment, we produced laser action at $1.3 \mu\text{m}$ by using fluorescence from the XeBr^* excimer to pump

$\text{C}_3\text{F}_7\text{I}$.⁶ Our apparatus is shown schematically in Fig. 7. We used a 130-kV Marx capacitor bank to drive a 1-m-long cold-blade cathode that emitted an electron beam with an energy of 230 keV and a current density of 3 A/cm^2 . The beam entered a gas cell through an electron transmission window of $13\text{-}\mu\text{m}$ Kapton over $25\text{-}\mu\text{m}$ titanium; the cell contained a mixture of 0.1-kPa Br_2 , 4-kPa Xe, and 200-kPa Ar.

A quartz laser tube (9-mm i.d.) was installed 3 cm from the electron transmission window and filled with 130-kPa $\text{C}_3\text{F}_7\text{I}$. The optical cavity for the laser consisted of a 5-m-radius, dielectric, coated mirror with maximum reflectivity at $1.3 \mu\text{m}$ and a 10-m-radius output coupler of 99% reflectivity. The resulting laser emission was detected on a calorimeter and a suitably attenuated photomultiplier tube. The laser output was 0.1 mJ in a 500-ns pulse. Because this was a proof-of-principle experiment, we did not try to couple the XeBr^* emission optimally into the laser tube.

By viewing a well-defined emitting volume at the midplane of the gas cell with the laser tube removed, we determined the efficiency for converting electron beam energy into XeBr^* fluorescence to be about 11%. We used SANDYL,⁷ a three-dimensional Monte Carlo electron transport code developed at Sandia, to calculate the electron-beam energy deposition in the cell. The excellent agreement observed between SANDYL predictions and calorimetry data lends strong credence to this efficiency figure.

Because the laser tube in this experiment was small, the $\text{C}_3\text{F}_7\text{I}$ was optically thin and absorbed only about 25% of the XeBr^* power spectrum. Larger tubes should significantly increase this absorption, although there are tradeoffs in attempting to optimize the system geometry because uniform gain is also desirable. If the laser tube is enlarged so that the medium is optically thick, absorption occurs primarily near the

Fig. 6. Coupling of XeBr^* emission to the absorption spectrum of $\text{C}_3\text{F}_7\text{I}$; σ is the absorption cross section.

Fig. 7. Experimental apparatus for electron-beam-pumped iodine laser. The gas cell contained a mixture of 0.1-kPa Br_2 , 4-kPa Xe, and 200-kPa Ar. The laser tube, filled with 130-kPa $\text{C}_3\text{F}_7\text{I}$, is 3 cm from the electron transmission window.

tube's boundaries and the central region remains unexcited; this produces a nonuniform gain where the energy output itself resembles a hollow tube. It seems plausible, however, that at least 75% of the XeBr^* emission could be effectively used for laser pumping, which would then result in converting about 8% of the electron beam energy into photolysis.

Having established a lower bound for fluorescence efficiency, we believe that the kinetic processes governing the production of XeBr^* warrant a concerted study. Optimization of these processes, along with aggressive development of electron-beam technology, may produce a high-energy-storage laser with an overall efficiency greater than 1%. The concept of an electron-beam-driven photolytic laser suggests the plausibility of scaling in the transverse dimension.

We are presently studying relativistic electron beams to find ways of providing more efficient and uniform energy deposition for pumping gas-laser media. One geometry that may be of interest, which we are pursuing, is shown in Fig. 8. The electron beam is directed through a cylindrical anode foil in the radial direction. The fluorescer gas is located between this foil and the laser tube, which is coaxial with the anode. Increased efficiency is obtained if the anode also serves

Fig. 8. Geometry of a proposed cylindrical electron beam for pumping gas-laser media.

as a reflector. Although small-scale (i.e., table-top) cylindrical electron beams have been demonstrated, larger versions will require significant development effort.

Another approach to producing these fluorescence bands is by electric-discharge pumping of rare-gas halide mixtures.⁸ It may be possible to enhance the efficiency of fluorescence production by this means, provided that an electron beam is present to stabilize the discharge in the highly electronegative mixtures containing halogens.

Future Applications. The high energy and average power eventually required for controlled thermonuclear power generation so far exceed today's technology that construction of intermediate laser systems is mandatory. A logical and necessary step toward developing the ultimate reactor laser is to identify, develop, and construct a high-energy-storage, short-wavelength laser capable of producing single-shot, 100-TW pulses. This facility would be used to explore

the physics of thermonuclear pellets under conditions approximating those of a pure-fusion reactor, but it would not entail the expense and technological complexity needed to build and operate a rep-rated (high-average-power) laser system. An upgraded SHIVA laser (from 20 to 100-200 TW) may serve this function. Farther downstream, on-site construction of a Laser Fusion Engineering Research Facility (LAFERF) has been proposed for the mid-1980's. Its design specifications also stipulate a 100-TW power output but with a 50-Hz repetition rate. The iodine photodissociation laser is a possible source for this facility. Other photolytic lasers of this type are also being considered.

Key Words: excimers; iodine - dissociation; iodine - fluorescence; iodine lasers; LAFERF; laser beams; laser beams - propagation; laser induced fusion; lasers; lasers - design; lasers - Lawrence Livermore Laboratory; lasers - optical pumping; narrowband excimer fluorescence.

FLUID JETS: ENHANCED CUTTING IN THE FAR ZONE AT LOWER PRESSURES

Recent studies at LLL have shown that rock and other hard materials can be eroded (cut) by water jets at relatively low pressures if the standoff distance is sufficiently long. For open-air water jets, the optimal distance is about 300 nozzle diameters. At this range, cutting threshold pressures are 10 to 25% of those in the near zone (~20 nozzle diameters). These lower pressures are especially important in drilling or mining hard materials; in the past, this work has required such high pressures that the availability of adequate pumps and piping has curtailed the use of jet drills.

For submerged jets, the far cutting zone does not exist because the jet momentum quickly diffuses. However, we have found that by ducting the jet in a tube, the far zone can be made available underwater. Some progress has been made in adapting this system to the high backpressures expected in deep drilling.

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Rising costs and the threats of energy and mineral shortages have focused attention recently on the need to speed up drilling and mining operations. Almost all of the nation's drilling and mining equipment is now employed, and there are many practical problems associated with mounting new operations with new equipment and crews. An obvious solution is to increase the productivity of the existing equipment if achievable at reasonable cost.

High-speed erosive water jets may be well suited to this purpose. These are jets operating at nozzle velocities of 25 to 250 m/s or even higher, with known ability to cut rock and other materials. Their potential for certain applications, such as for excavating mining tunnels and storage caverns, producing minerals like oil shale by underground hydraulic-mining techniques, and even cutting hard-to-machine materials in fabrication shops, is well established. Jets may prove equally useful in oil- and gas-field drilling, particularly for special or costly drilling efforts (e.g., geothermal-well development, offshore drilling, and

FLUID JETS: AN OVERVIEW

The use of fluid jets to cut rock and other materials is not new. Water jets were employed a century ago in mining operations, though their use was not widespread: the materials for high-pressure pumping systems had not yet been developed, and pumping efficiencies were low. Nonetheless there was serious interest in the processes involved, as evidenced by Rayleigh's theoretical treatise in 1878 on instabilities in fluid jets.

After the turn of the century, stronger, more durable materials and improved pumping efficiencies stimulated interest in high-pressure systems and high-speed jets: those having average nozzle velocities of 25 m/s or higher. Other applications were now conceived, such as for drilling oil wells and cutting metals and fibrous materials like asbestos. The two decades before World War II produced experiments and several detailed theoretical studies including Weber's 1931 derivation of the mathematical relations for surface waves in a cylindrical jet. Specific uses also emerged for high-speed jets, along two principal lines of development. The first was for injecting fuel into the combustion chambers of diesel engines, with emphasis on developing jets that would atomize the diesel fuel more efficiently. The second, promoted largely by the petroleum industry, was for augmenting rotary drilling operations. High-speed fluid jets were found to increase the production rate, helping not only to cut the rock but also to remove rock fragments from the bottom of the bore hole.

Since then, considerable money and effort have gone into developing fluid jets, including major industrial research programs and an expansion, especially in this decade, of theoretical studies. However, for reasons discussed in the accompanying article, the technological and economic promise of fluid jets has not yet been fully realized. The chief technological obstacle has been the apparent inability of jets to cut certain very hard rocks and other materials at practical pressures.

Based on the research described here, we at LLL believe that significant progress has been made toward overcoming this obstacle.

underreaming). Considerable work has already gone into developing practical jets and cutting schemes.

"Near-zone cutting," at about 20 nozzle diameters, has been the standard with jet drills. However, recent studies at this Laboratory have established that "far-zone" cutting by water jets, at about 300 nozzle diameters, is much more effective under certain very practical conditions. In the far zone we have succeeded in cutting dolomites, alumina, and even boron carbide at less than the *usual* working pressures for field equipment. By comparison, during a large field experiment, dolomite was unaffected by jets cutting in the near zone even at the very upper pressure limits of specially modified drilling equipment.⁹

By laser photography and other means, we are now proceeding with fluid-mechanics studies to explain some of the phenomena we have observed. Various theories have been advanced. We have also developed a shrouded nozzle that enhances the effectiveness of the jets used underwater.

Jet Drilling

Nowhere is the need to accelerate operations felt more keenly than in oil and gas exploration, where a shortage of drill-rig capacity is considered a limiting condition on our national efforts to achieve energy self-sufficiency.¹⁰ Faster drilling could help offset a recognized shortage of drill rigs.

Some 90% of our oil and gas wells are now drilled by rotary bits, occasionally in conjunction with fluid jets (see the accompanying overview). Rotary bits are versatile performers of proved utility, but they have two serious drawbacks: they cannot deliver more than about 37 kW (50 hp) to the bottom of the hole, and the costs for installing new bits can become overriding, particularly for deep wells. Attempts to deliver more power to the bit — to hasten the drilling — increase the abrasion and bearing wear, with overall diminishing returns. Twenty or more bit replacements while drilling a 3000-m well are not unusual. The bits themselves may cost up to \$5 000 each, and the costs for lifting the drill string — each time — may run over \$50 000 depending on the depth of the well.

There are other situations in which rotary bits are expensive to use: for example, offshore or in the Arctic where surface conditions increase the operational difficulties, and in geothermal strata or very hard rock, where underground conditions are unfavorable. In such applications an alternative could be useful.

Among the most promising alternatives proposed to date have been the spark bit, which cuts by means

Table 3. Bit comparison^a

Drill	Maximum power delivered to rock, kW (hp)	Maximum cutting rate, cm/min
Rotary bit	19-37 (25-50)	14-85
Spark bit	75-150 (100-200)	35-140
Fluid jet (no additives)	750-1500 (1000-2000)	35-140

^aFor a 20-cm-diam hole in rock with a compressive strength of 500-1000 kg/cm². From W. Maurer, *Novel Drilling Techniques* (Pergamon Press, Ltd., New York, 1968).

of an electrical discharge, and the high-speed water jet. Table 3 compares these with the rotary bit in two regards: power delivered to the well bottom, and maximum cutting rate. The data are based on laboratory tests and, for the jet and the rotary bit, also on extensive field tests. Neither the spark bit nor the jet uses power as efficiently as the rotary bit, but the cutting-rate potential for each is greater. This is more important. Inefficient power use is not particularly significant because power costs are relatively small compared with overall costs.

Despite this favorable comparison, neither the spark bit nor the jet thus far has been considered competitive with the rotary bit. Two technical problems with the spark bit — electrical-power delivery to the bit and its use in a fluid environment — are as yet unresolved. For reasons associated with the jets' high-pressure fluid supply system, the average drilling rate with jets has been lower, in practice, than with rotary bits. The chief problems have been the maintenance of high-pressure mud pumps and piping (compounded when abrasives or polymers are used) and the seeming inability of jets to cut very hard rocks, such as dolomitic limestones, at pressures that are practical for conventional pumps and pipes.

Oil companies have spent millions investigating jet drills. They have tested different nozzle designs at various pressures, concluding that jets are attractive for certain rock strata and operating conditions but are not universally usable at practical pressures. In specific terms, the very upper pressure limit for their equipment is about 100 MPa (15 000 psi); even then, special pumps are required. Pressures beyond 100 MPa require new equipment — mud pumps and piping — which the companies have considered economically unjustifiable. Nevertheless, faster drilling with fewer replacements has been demonstrated with jets. In one test,¹¹ jetted abrasive particles drilled a

2700-m well in one-third less operating time than rotary bits (200 vs 300 h), with one-third fewer drillhead replacements (13 vs 20). The superiority of the jet drill increased with depth.

The above work, however, was conducted in the near zone: that is, at standoffs of about 6 cm for a 3-mm-aperture nozzle. The jet stream at this distance probably cuts by overcoming some gross mechanical strength properties of the medium. Our studies, by contrast, at pressures lower than the above, have shown that the optimal drilling distance for a 3-mm nozzle in air is about 90 cm. At this range and these pressure levels, one finds a peak of drilling activity, analogous to the action of miniature jack hammers, after more than 200 nozzle diameters (about 60 cm) of almost no activity. The discovery of this far-zone peak activity is not new,¹² but experiments of comparable magnitude have never before been reported. Our jets, without abrasive or polymer additives, have cut dolomite at pressures of 34 MPa (5 000 psi), substantially less than the maximum pressures of previous tests.

While these results are promising, we must note that the data relate to jets in air and thus are not directly applicable to the liquid environment found in well drilling. Even though we expect to get similar results with jets operating in liquid, there will still remain the tasks of solving the practical problems of field operations.

LLL Studies

From our earlier work in optimizing nozzle shapes, investigating flow conditions, and observing the best conditions for erosion, we have now moved to analyzing far-zone cutting effects, developing the

shrouded nozzle, and studying the relevant fluid mechanics.

Reduced Nozzle Pressures. Table 4 summarizes our findings on the minimum nozzle pressures needed to induce erosion in the far zone. Compared with the required near-zone pressures, the reductions range from 10 to 25% with the upper limit in doubt because dolomite, alumina, and boron carbide were unaffected in the near zone even at our maximum test pressure of 100 MPa. The measured compressive and tensile strengths in this table were obtained from unconstrained sample tests in air. These values are given more to describe the material than to imply a definitive connection between them and the jet supply pressure at failure, because no regular connection of this kind is known.

Figure 9 shows our results from directing a 2-mm-diam jet onto Indiana limestone targets at 19 nozzle diameters in one test series and 318 nozzle diameters in another. The nozzle pressure varied from near the upper limit of the test apparatus to a pressure too low to mark the limestone. In each case we measured the volume of the crater and compared it with the jet energy expended to produce it.

As shown by this figure, our experience in these tests is that although cutting in the far zone uses the jet power less efficiently than in the near zone, it can be accomplished at much lower nozzle pressures. The significance of this pressure differential, we believe, is that the real cost of supplying a unit of jet energy at 40 MPa may be many times that of supplying the same energy at 10 MPa, depending on details of the operation. This point is illustrated in another form in Fig. 10, which shows that we were able to cut dolomitic limestone in the far zone though not without

Table 4. Threshold nozzle pressures for near- and far-zone cutting of various materials (maximum pressure 100 MPa)

Material	Dry strength, MPa		Cutting threshold pressure, MPa	
	Compressive	Tensile	Near zone (20 nozzle diam)	Far zone (300 nozzle diam) ^a
Indiana limestone	62.6	5.4	31	3.4-6.9
Westerly granite	165	11.5	41-48	7
Blair dolomite	522	7.6	>100 ^b	<34
Alumina (Al ₂ O ₃)	2800	210	- ^b	<69
Boron carbide (B ₄ C)	2900	310	- ^b	<69

^aAt 300 nozzle diameters, the centerline dynamic pressure is about 40% of the nozzle pressure.

^bBlair dolomite, alumina, and boron carbide were undamaged in the near zone even at maximum pressure.

difficulty. Because the dolomite cannot be visibly worked by our apparatus in the near zone, far-zone

Fig. 9. Specific energy of removal for Indiana limestone as a function of nozzle pressure for near- and far-zone cutting, jets operating in air. The arrow (upper left) indicates an indeterminate upper limit.

Fig. 10. Specific energy of removal for Blair dolomite as a function of nozzle pressure for far-zone cutting (318 nozzle diameters), jets operating in air. In the near zone (19 nozzle diameters), no erosion was observed with nozzle pressures up to 100 MPa (15 000 psi).

cutting is patently better. We believe that other, similar situations may arise in the practical application of jets.

In these tests, the energy costs for drilling were related to nozzle pressure. It is worth noting that although the dynamic pressure on the jet's centerline at 20 nozzle diameters is nearly the same as the nozzle pressure, it is only about 40% of the nozzle pressure at 300 nozzle diameters. Apart from the contrariness of associating more damage with less pressure, this fact suggests that proper design might lead to still better results. Other things being equal, the far-zone cutting action increases with increasing local dynamic pressure. So if this action could be induced closer to the nozzle where the dynamic pressure is higher, the supply pressure needed for comparable cutting might be further reduced.

Shrouded Nozzle. The above phenomena refer to water jets in air, whose useful applications are limited. In deep well drilling, for example, the working fluid and environment are drilling mud. As shown in Fig. 11, which depicts some measurements by others for water jets submerged in water, the dynamic pressure drops to 40% within 10 to 15 nozzle diameters compared with 300 diameters in air. Far-zone cutting just does not occur for a simple submerged jet.

Fig. 11. Attenuation of centerline dynamic pressure of a submerged jet as a function of distance from the nozzle (after Kondo, Fuji, and Syoji¹³).

Fig. 12. Specific energy of removal for Indiana limestone as a function of nozzle pressure for shrouded, submerged nozzles.

However, by adding an extension to the nozzle, which we call a shroud, we have been able to reproduce the air results with a submerged jet. Figure 12 shows the cutting performance of this device in a water tank with relatively low-pressure heads imposed on the water. The shroud is a duct of somewhat larger diameter than the nozzle, its length approaching the standoff distance. The cutting efficiency of the shrouded jet seems to be the same as for the open-air jet, although the lowest threshold pressures have been obtained at standoffs of about 200 rather than 300 nozzle diameters. In air, cutting at this distance required more than twice the energy. Apparently one effect of the shroud is to shorten the distance to the far-cutting zone.

A principal effect of the shroud is to induce two-phase (gas and water) flow. This fact was confirmed by direct observation through a transparent shroud and was indicated by the low static pressures measured at several points along an instrumented shroud. Flow from the nozzle through the shroud and into the working chamber can be characterized as flow through an intermediate sudden expansion, and the pressure in the intermediate passage can be much lower than in the working chamber. There is a limit, however, to the backpressure against which the flow can diffuse and still have two phases upstream. The solid line in Fig. 13 shows an upper bound for cavitation as a function of the shroud-to-nozzle area ratio. Above this line, momentum could not be conserved even if there

were no losses and the velocity profiles in the cross sections were optimal.

The circles in Fig. 13 indicate observed conditions in the shroud for the tests we have run. Two-phase flow for the length of the shroud was noted in the region occupied by the open circles. The partly open circles indicate some gas phase near either the nozzle or the working end, depending on how the circle is eclipsed. If we assume that submerged far-zone cutting depends on the conditions denoted by open circles, the highest feasible backpressure we have demonstrated is about 21%. We cannot presently take advantage of the theoretical possibilities of area ratios approaching 2 because of large frictional losses in the closer-fitting shrouds. We must also yet assess the target-cutting characteristics of the jet under such backpressures.

Fluid Mechanics. By means of a photographic system that uses a pulsed ruby laser with a 30-ns pulse duration, we have been studying the behavior of water jets by shadowgraph photography. As shown in Fig. 14, the pulsed laser produces an extremely detailed photographic record of the jet structure, far more definitive than flash photography. Laser photography has allowed us to see, for the first time, a foglike zone of fine water stringers along the surface of the jet's core. Other instabilities, predicted by theory, characterize jets flowing either at subsonic or supersonic speeds with respect to the ambient air. Understanding such instabilities is one goal of our fluid-mechanics research.

We are also proceeding, in preliminary fashion, with calculational studies aimed at producing a reliable theory to predict cutting. Examination of the LLL computer codes suggests that existing codes may be adaptable to jet-cutting applications.

As regards the specifics of enhanced far-zone cutting, we offer no analysis at present but list some physical observations that may be related to the phenomena and with which analysis should be consistent:

- Metal exposed to a jet with increasing standoff distances first shows an erosion ring of approximately jet diameter that ultimately coalesces to a disc, becomes larger, and deepens.
- Point measurements of the dynamic pressure across the jet with increasing distances show that, although the pressure profile is a smooth bell-shaped curve near the nozzle, pressure irregularities appear near the edges of the distribution further away from the nozzle. These irregularities increase both in amplitude and extent with increasing distance. Our

Fig. 13. Two-phase flow in the intermediate sudden expansion that characterizes shrouded nozzles. The symbols refer to conditions described in the text. Partly open circles denote the region of apparent cavitation.

pressure probes have been destroyed at standoff distances near 300 nozzle diameters.

• The gases evolved are only partly water vapor. A shroud 300 diameters long operating underwater produced a stream of gas bubbles that did not condense as they floated up and presumably were air bubbles. Because the system was not vented to atmosphere at any point, it seems that the gas must have been carried in solution by the jet stream and come out of solution in a relatively short time.

Gas evolution from the jet stream is one theory that might account for far-zone cutting. In the above underwater test, the transit time in the shroud during which the stream was at low pressure was 2.7 ms. We measured the total pressure of the gas mixture in the shroud (3.066 kPa) and the partial pressure of the noncondensables (1.6 kPa), deducing 1.466 kPa as the partial pressure of the condensables. Assuming the noncondensable gas to be air and the condensable vapor to be water, we then calculated the volumetric fraction of air in the gas mixture to be 34%. If these

assumptions are correct and a similar evolution of dissolved air takes place whenever water vapor is produced, the dissolved gases could contribute heavily to far-zone erosion.

Vacuum cavitation like that in the near zone is a second possibility, and physical breakdown of the jet into droplets that do the actual drilling is a third. We do not yet know which of these factors are involved or to what extent.

Future Work

We believe there is a reasonable chance of significantly lowering the required working pressure for practical jet erosion by a relatively simple change of the nozzle. More data are needed, both analytical and experimental, before the economic realities can be assessed. Experimentally, we intend to set up both the jet and the target so that deep drilling can be simulated; the jet will work into liquid backpressures up to 34 MPa, and the target will be under the appropriate triaxial stress.

Fig. 14. Shadowgraph produced by a pulsed ruby laser (above) provides a far more detailed record of jet structure than a conventional flash photograph (below). The laser pulse duration was 30 ns and the flash duration approximately 2 μ s. The nozzle orifice (1 mm) and jet velocity (about 200 m/s) are the same in both views.

Additives would be a new area of experimentation for us. We plan to explore the effects of additives with respect to at least four possible advantages: (1) fibers or long-chain polymers may decrease the friction of the jet in close-fitting shrouds so that higher backpressures can be handled, (2) fibers or long-chain polymers may contribute directly to the cutting process by mechanically point-loading the target, (3) an admixture of a relatively insoluble gas such as helium may produce higher jet velocities, and (4) the addition of a soluble gas such as carbon dioxide may draw the far cutting zone into regions of higher dynamic pressure.

The properties of drilling mud as a working fluid in the far cutting zone are another additive problem to be explored. If the results with water continue to be encouraging, it should be profitable to change over to drilling mud with and without abrasive particles, to get pertinent data for deep drilling applications.

Analytically, we hope to achieve an understanding of the causes for enhanced far-zone erosion and to determine which target-failure mechanisms are being activated. Jet turbulence and the dynamics of nucleation and growth of gaseous regions in the jet — both condensables and noncondensables — are promising avenues for immediate research.

Key Words: fluid jets; water jets; drilling; cutting — far zone; shrouded nozzle; fluid mechanics.

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ENERGY PERSPECTIVES;⁷

NONELECTRICAL USES OF GEOTHERMAL RESOURCES

Nonelectrical uses of geothermal resources around the world now account for more usable energy than existing geothermally powered electrical generating plants. Applications include space and water heating, refrigeration, drying, industrial processing, agriculture, animal husbandry, and even aquaculture (the cultivation of aquatic species). The chief advantages of nonelectrical recovery are a high efficiency of heat utilization and the capability for using geothermal resources that are too low in temperature (50 to 160°C) to generate electricity efficiently.

Although nonelectrical applications in the U.S. are now quite limited, there is a sizeable potential for expansion.

As reported recently in *Energy and Technology Review*,¹⁴ this Laboratory is committed to developing the technologies needed for extracting electrical power from geothermal sources. Our concept is the total flow process, utilizing high-temperature brines (160 to more than 300°C). We believe that electrical power from geothermal energy may ultimately make a small but important contribution to total U.S. energy supplies. Various other nations are engaged in similar developments.

There are also many nonelectrical uses for geothermal resources, most of which have been extensively developed elsewhere in the world. For NATO's Committee on the Challenges of Modern Society, we have just completed a comprehensive survey of global resources and applications. We reached several conclusions:

- Geothermal resources are widely distributed throughout the world.
- Extraction presents no serious technical problems.
- A wide variety of economically viable nonelectrical applications currently exists.
- Disposal of spent geothermal fluids has a significant ecological impact. Reinjection appears to be the best alternative.

The results of this survey have been published.¹⁵ This article briefly summarizes our findings and

discusses current and potential nonelectrical uses for geothermal resources, some of which may be appropriate for the U.S.

Global Resources

For nonelectrical applications, the appropriate temperature range for geothermal fluids is considered to be 50 to 160°C, the lower temperature being the minimum practical for greenhouse heating and the upper temperature being the threshold limit for economic use of the fluids to generate electricity.

As shown in Fig. 15, geothermal fluids occur widely under all continents. Such disparate locations as Iceland, New Zealand, and Hungary all have sizeable resources. Those in the Soviet Union are immense; estimates suggest that perhaps half the Soviet land mass is characterized by relatively low-temperature fluids appropriate for nonelectrical applications. In the U.S., 1185 areas of hot springs are known, of which possibly several hundred are commercially exploitable. Present production is not large, accounting for only 15 MW of heat-rate usage compared with our total annual electrical-power production of 400 000 MW (from all sources). Estimates put the maximum probable nonelectrical recovery from known U.S. resources at perhaps 1500 MW per year.

The investigation of geothermal resources is still at its inception. We can expect to find a great number of additional resources similar to those already discovered.

Applications

Compared with the power derived from geothermally operated electrical generating plants (1100 MW with an additional 600 MW planned), that associated with nonelectrical applications throughout the world now amounts to more than 5500 MW. Note that this comparison is not between like activities: nonelectrical applications have a conversion efficiency of about 85% vs about 10 to 15% for electrical uses. Thus the nonelectrical applications thermodynamically represent a much more efficient use of the resource.

As described in the following paragraphs, nonelectrical uses include residential, commercial, industrial, and food-related applications. Figure 16 shows the general worldwide distribution of these

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Fig. 15. High-temperature geothermal regions of the world (those considered suitable for electric-power production as well as nonelectrical applications). Data from Geonamics, Inc., Hempstead, N.Y.

applications. Although the individual uses are discussed separately, distribution systems could be integrated to serve more than one function. Iceland, for example, has already done this to a limited extent.

Residential and Commercial. Space heating and other residential uses are perhaps the most promising nonelectrical applications because the required fluid temperature is relatively low (50 to perhaps 75°C). These uses are now quite widespread, representing some 400 MW average annual energy consumption. Water heating, drying, space cooling, and some types of refrigeration hold promise.

In most nations, the amount of energy consumed for residential and commercial purposes is a significant fraction of the total. In the U.S., for example, that consumed for space heating alone is about 18% of the total, while water heating, space cooling, and refrigeration consume an additional 7.5%. In Denmark, an extreme case, space heating accounts for 43% of the total national energy consumption. Clearly, if geothermal resources could be utilized for these

purposes, a significant savings of conventional energy would obtain.

The two possibilities for heating systems are district heating and individual systems. The former — distribution of thermal energy in the form of steam or water through networks of insulated piping — can economically supply large markets for space heating. District heating is well established in principle, several nations having maintained district systems for many years (although usually fueled by fossil fuels). The two most common types of residential heating systems — warm/hot water systems and forced air systems — are readily adapted to geothermal energy.

An important consideration is economics. Geothermal space-heating systems are most economical in high-latitude regions characterized by high load factors and high costs for fossil fuels. Also, it is more expensive to heat single-family dwelling areas than apartment areas. In the U.S., because of lower load factors, it would be impractical to heat single-family units with district heating. Multiunit dwellings (between 10 and 40 units) might prove practical.

The most significant existing geothermal district-heating system is that of Reykjavik, Iceland. This municipal system, accounting for well over half of Iceland's total space heating from geothermal power, supplies about 11 000 homes (99% of the city) and serves about 88 000 residents. It also heats greenhouses and multistory buildings. The climate in Reykjavik is especially suited for a district system because heating is required year round and the peak monthly load in January is only 2.3 times the minimum monthly load in July. Typical heating costs are approximately \$200 per family per year. At 1974 oil prices, the corresponding costs for petroleum fuel would be about \$800 annually.

Russia, France, and Hungary also use district heating but on a much smaller scale.

The two most significant individual-system applications are a hotel in Rotorua, New Zealand — unique in that it is the only geothermal

system designed for both comfort heating and cooling — and a sizeable development in Klamath Falls, Oregon, that involves some 500 locations served by 400 wells. Klamath Falls has had individual space heating from geothermal energy since about 1930. The predominant method (for both space heating and domestic hot-water heating) is a downhole heat exchanger, usually by means of standard black pipes of suitable length. The various systems now supply heat at an annual rate of 5.6 MW.

Industrial. Although relatively little has been done to date with using geothermal steam and hot water directly in industrial processes, climbing fossil-fuel costs and increasingly available geothermal energy sources should spur this development. Applications include simple process heating, evaporation, drying, distillation, refrigeration by absorption machines, sterilization, washing, and de-icing (as for mining

Fig. 16. Worldwide nonelectrical applications of geothermal energy. Iceland leads in residential and commercial applications with about 200 to 225 MW, followed by the Soviet Union with about 100 MW. Significant industrial applications include pulp and paper manufacturing in New Zealand (100 to 125 MW), light manufacturing in Iceland (35 MW), and chemical manufacturing in Italy (19 MW). Largest food-related applications are in the Soviet Union (5011 MW for greenhouses) and in Hungary (160 MW for greenhouses and 203 MW for animal husbandry). U.S. applications include about 15 MW for space heating, 0.5 MW for greenhouses, and a small amount for chemical processing.

operations). Another promising line of development is minerals recovery from geothermal brines. The number of industrial plants now using geothermal resources is small, but the total power consumption is significant: 150 to 200 MW.

The two largest industrial applications, at present, are a pulp, paper, and wood processing plant in New Zealand and a diatomaceous-earth plant in Iceland. The plant site in New Zealand was chosen because of the availability of geothermal energy; this was the first such major industrial development. Exploration commenced in 1952, and the plant started production in 1960.

The diatomaceous-earth plant at Namfjall, Iceland, developed around geothermal energy because conventional energy resources would have been too costly. Following the discovery of rich, high-grade diatomite deposits on the bottom of nearby Lake Myvatn, technical and economic studies indicated that only by using cheap geothermal energy from a high-temperature geothermal field could the recovery and drying process be made economically competitive with conventional diatomite recovery from relatively dry land. The plant began production in 1967 and has a current annual production rate of about 22 000 tonnes.

Food-Related Applications. The use of geothermal fluids in agriculture, animal husbandry, and aquaculture has the potential for producing vast quantities of food at great efficiency and reduced costs. As shown in Fig. 16, several nations are now applying geothermal resources to these activities.

The most extensive use has been for greenhouses, especially at high latitudes where the growing seasons are short. Iceland, with a short growing season and low sunlight intensity, leads in this development. Both the Soviet Union and Hungary have built sizeable numbers of geothermally heated greenhouses for vegetables and horticulture. In the Soviet Union alone,

the annual production of vegetables from geothermally heated greenhouses is more than 1 million tonnes.

Geothermal fluids are not used as extensively in animal husbandry but the uses are more diverse: for example, cleaning, sanitizing, and drying animal shelters and wastes, in addition to space heating. In Hungary, animal-husbandry applications now account for 203 MW of geothermal energy. Geothermal fluids are being used in Japan to maintain optimal temperature conditions for alligator and crocodile breeding.

Both Iceland and Japan have small facilities related to aquaculture involving, for example, the breeding of eel, carp, and salmon.

Future Prospects

It has been suggested that the major problem thus far limiting the use of geothermal resources for nonelectrical applications has been cultural inertia due to the newness of geothermal energy.¹⁵ In most of the world, the technology for such applications has not been systematically developed and promoted. Only in Iceland and New Zealand have nonelectrical geothermal applications become a principal national energy-technology effort.

The French recently have been striving to overcome this inertia, completing, for example, a project to heat 3000 apartments by groundwater at normal temperature for its depth of occurrence. This sort of application might be particularly appropriate for the U.S., where the nonelectrical uses of geothermal resources will never approach the national need for space heating. If some practical scheme could be developed for exploiting normal-gradient hot water, the realization of its enormous heating potential might someday be significant in meeting U.S. requirements.

Key Words: geothermal; geothermal - nonelectrical uses; geothermal - worldwide resources; geothermal - district heating.

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14. The LLL geothermal energy development project is described in the August 1975 *Energy and Technology Review* (UCRL-52000-75-8), p. 1.
15. J. Howard, ed., *Present Status and Future Prospects for Nonelectrical Uses of Geothermal Resources*, Lawrence Livermore Laboratory Rept. UCRL-51926 (1975).