147
12-8-77

100

16.1648

Energy and Technology Review

MASTER

Lawrence Livermore Laboratory

July 1977

CANCER RESEARCH

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

July 1977

Energy and Technology Review

Lawrence Livermore Laboratory

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

Scientific Editor:

Henry D. Shay

General Editors:

A. Paul Adye

M. Beth Bathgate

Richard B. Crawford

Kent L. Cummings

Larry Gottlieb

Coralyn K. McGregor

Jane T. Staehle

BRIEFS

ii

Short items reporting on recent developments.

TMX: A NEW FUSION PLASMA EXPERIMENT

1

LLL's tandem mirror experiment (TMX) is another step toward achieving economically feasible power production from a mirror fusion reactor.

TAMING GEOTHERMAL BRINES FOR ELECTRICAL POWER

10

Extracting energy from high-salinity, geothermal brines now appears feasible. Acidification shows great promise for taming the brines.

FLOW CYTOMETRY IN CERVICAL CANCER DIAGNOSIS

20

Rapid prescreening and early diagnosis of cervical cancer may be possible using flow cytometry with gynecological samples.

PROBING NUCLEI WITH LLL'S ELECTRON LINEAR ACCELERATOR

27

We use our 100-MeV linear accelerator to expand our understanding of fundamental nuclear physics in a variety of applications.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, 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.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

BRIEFS

SHIVA FIRST-ARM PERFORMANCE

On August 3, 1977, we successfully fired a 1-ns pulse through the first of 20 arms on the Shiva laser—the 10-kJ facility nearing completion at LLNL. The output energy, as measured with a calorimeter, was 526 J. A photograph of the near-field beam showed very little beam breakup. This indicates that more than 90% of the energy was focusable onto a target. The small amount of dirt-related noise, which resulted in some coating damage on one lens, will be eliminated by increased spatial filtering and cleaning. Thus, on a single-chain basis, Shiva exceeds its design-rated performance.

Alignment of the remaining 19 beams should be straightforward, since the system is already almost completely aligned from the oscillator through the 20-beam splitter array up to the input aperture of each laser chain. The digital control system, a new departure for pulse-power control, performed satisfactorily, and the automatic beam alignment system is now working better than expected. Beam pointing and centering stability is excellent. We are on schedule to fire a full 20-beam, 10-kJ, 1-ns pulse in October, with upgrading to over 20-JW operation in 1978.

Contact John R. Holmstedt (246-2292) for more information on this project.

NUCLEAR ENERGY

TMX: A New Fusion Plasma Experiment

The primary goal of the magnetic fusion energy program at LLL is the development of a technically and economically feasible approach to the generation of fusion energy. Results from our earlier 2XII-B experiment lead us to believe that a fusion power plant based on a mirror system is technically feasible, assuming a favorable extrapolation to plasmas of reactor size. Achieving economic feasibility is more difficult. For power-producing applications, a reactor needs a large Q , the ratio of fusion power output to the power injected to sustain the system. In a conventional mirror reactor, the fusion power is only about equal to the power injected by the neutral beams—that is, Q is only about unity. A new idea, the tandem mirror concept described in this article, promises to increase this gain, enhancing Q by at least a factor of 5.

Attendees of an international workshop on Q enhancement in mirror fusion reactors, held at LLL in September 1976, selected the tandem mirror as one of the two most promising approaches among many alternatives for improving Q in mirror reactors. A subsequent proposal by LLL to build the tandem mirror experiment (TMX) was sent to

ERDA in January 1977, was reviewed by an ERDA panel in February 1977, and was approved for funding in March 1977. Enthusiasm for the tandem mirror idea is evidenced by the rapid transformation of the new idea into a proof-of-principle experimental facility at LLL that will cost \$11 million. Tandem mirror experiments are also under construction or being planned in the Soviet Union, in Japan, and at the University of Washington.

GENESIS OF THE TANDEM MIRROR

The tandem mirror configuration was suggested by Dimov and his coworkers at Novosibirsk¹ and independently by Fowler and Logan at LLL.² It is an extension of an earlier idea by Kelley.³

What is the new idea? A tandem mirror uses two simple, or conventional, mirror machines as basic components, placed at either end of a series of cylindrical coils that make up a solenoid (Fig. 1). Each mirror machine, or end cell, provides a minimum- B magnetic field—that is, the intensity of the field increases in every direction away from the geometric center of the machine. Particles are trapped in the central area of least intensity called the magnetic well. Ions are thus confined radially in a spiral motion around the field lines and are reflected longitudinally between the magnetic mirrors at either end. Ions having velocities with the largest

²Contact B. Grant Logan (Ext. 4728) for further information on this article.

Fig. 1. The tandem mirror machine. Coils are copper-colored. Inside the coils is the sausage-shaped plasma, shaded red. Note the characteristic double-fan shape of the plasma in the end cells caused by the magnetic field of the baseball coils. The end cells stabilize the solenoid plasma and provide longitudinal confinement.

component perpendicular to the magnetic field lines are trapped between the mirrors in the two end cell for a length of time called the ion-ion collision time. This is roughly the time it takes the ions to scatter enough for the parallel component of their velocities relative to the magnetic field lines to become sufficiently large to carry them through the mirrors and out of the system.

For reasons that will be explained in more detail later, the mirror machines at either end of the central solenoid in a tandem mirror machine serve as "plugs" because they act to reflect ions escaping

from the ends of the solenoid. In theory, ions in the solenoid can be confined for many collision times, long enough for many fusion reactions to occur and result in a high fusion-power yield. A tandem mirror combination thus allows a solenoid to be used for confining the main fusion plasma—and a solenoid is the ideal simple and potentially economical core for a magnetic fusion reactor.⁴ (The box on p.4 contains a brief discussion of the potential role of mirror fusion reactors and the progress made thus far in their development.)

Figure 1 shows the essential parts of a tandem

Fig. 2. Density and field profiles of a tandem mirror machine. Four successive peaks in the magnetic field (yellow) connect the solenoid in the center to two mirror machines in tandem. The high-density plugs are stirred and maintained by injected neutral beams; the lower-density solenoid is maintained by a gas feed. The magnetic field strength (yellow line), the density of the hot ions in the plug (red), the density of the warm ions in the solenoid (orange), and the density of the electrons (blue) are shown as they vary with distance along the axis of the tandem mirror system. The difference between the densities of the plug ions and the electrons leads to the formation of an electrostatic potential well. This well confines both ions and electrons, which are reflected back into the solenoid at the positions shown.

mirror machine. Coils having a configuration resembling the seam of a baseball are placed at either end of the solenoid. Beams of high-energy neutral atoms are injected into the baseball coils; the result is a high-density, mirror-confined plasma in each coil. A gas composed of deuterium and tritium (the fusion fuel) is injected into the solenoid. Hot electrons that pass freely between the central cell and the end cells ionize the injected gas, creating and maintaining a plasma in the central cell that has a lower density than the plasma in the end cells. The ions in the central cell are confined radially by the solenoidal magnetic field and longitudinally by the mirror machines at either end. Although continuous input power is required to sustain the plasma in the end cells, the overall Q can be high because the

volume of the plasma in the central cell greatly exceeds that in the end cells.

The longitudinal confinement provided by the mirror machines results from a difference in the electrostatic potentials of the plugs and the solenoids, called a "potential well," that confines ions in the solenoid. To illustrate how this well is formed, we show in Fig. 2 the variations with distance along the axis of the tandem mirror system of the magnetic field strength and the various particle densities.

Because of their smaller mass and larger velocity, electrons tend to scatter and to escape along the magnetic field lines from the plugs and solenoid much faster than the ions. As a result (see Fig. 2), the electron density tends to drop slightly below the

MIRROR FUSION REACTORS

Fusion power is attractive because its fuels are abundant and it is potentially clean. If fueled with deuterium and tritium, it would depend on the resources of deuterium and lithium-6, both of which are plentiful. Deuterium may eventually be the sole fuel, and it is extremely abundant: the amount found in the oceans could sustain the present world energy consumption for 100 billion years. While fusion power presently involves radioactive materials—tritium and irradiated walls—its evolution will quite likely lead to a source of energy less hazardous than any other, except solar power.

For fusion power to become an economic reality, however, practical methods must be found for: (1) heating fusion fuel (plasma) above its ignition temperature, (2) confining this superhot plasma long enough for energy output to exceed input, and (3) converting the released energy to usable forms (electricity and process heat). Scientists have been working on these problems for more than two decades now, and, while many scientific and economic problems have yet to be resolved, major progress has been made.

One approach to fusion research is magnetic confinement, which calls for containing very hot, high-density plasma in specially shaped magnetic fields. There are two basic confinement configurations: open-ended machines (mirror or theta pinch) and closed toroidal machines (Tokamak). In U.S. magnetic-confinement research, LLL has the prime responsibility for pursuing the mirror machine. Mirror fusion reactors offer the advantage of high power density coupled with relatively small size; that is, a mirror reactor may be successful at the few hundred megawatts level, one-tenth the anticipated toroidal machine levels. Also, the mirror concept is capable of steady-state dc operation, an important factor in achieving the ultimate fusion energy goal: commercial electric power generation.

The 2X11B experiment at LLL has shown that dense, hot plasma can be confined, free from disruptive instabilities, for extended times. Mirror researchers are therefore increasingly turning their attention to a different problem, that of economics. To be economically practical, a fusion reactor obviously must produce more power than it consumes: a simple index of this power gain is the quantity Q , defined as the ratio of fusion power output to the power input to maintain the fusion reaction. The higher the power of Q , that is, the greater the Q enhancement, the better. One idea advanced as a promising approach to Q enhancement is the tandem mirror, a configuration in which fusion plasma is confined in a long solenoid terminated at each end by a mirror machine. The accompanying article describes the tandem mirror concept and the proof-of-principle experiment being conducted at LLL.

ion density in both the plugs and solenoid. This difference in density is maintained because both the plugs and the solenoid then develop enough positive charge with respect to the end walls of the system to keep the electron loss rate equal to the ion loss rate. Only a very slight difference between the ion and electron densities is required to set up large positive potential energies that are several times the electron temperature. Since the positive potential increases with the density of the electrons, and since the electron density in the plugs is higher than that in the solenoid, the plug plasmas are more positive than the solenoid plasma.

This potential difference between the plugs and the solenoid makes the potential barrier that confines ions in the solenoid. Depending on the

plug-solenoid density ratio and the electron temperature (which determines the magnitude of the potential well), it can take a hundred ion-ion collision times before the ions overcome the potential barrier, leave the potential well, and leak through the plugs.

The plugs also provide a sufficient average centering magnetic force to stabilize the plasma in the solenoid. Without the plugs, the shape of the field at the ends of the solenoid would allow sideways motion of plasma.

In a fusion reactor burning deuterium and tritium in the solenoid, fusion alpha particles (helium-4) born in the solenoid plasma from the deuterium-tritium reaction can provide a large fraction of the heat input required to maintain the tem-

peratures of the electrons and the solenoid ions. The rest of the required energy input to the solenoid plasma can originate with the energetic ions in the plugs. These ions lose energy to the electrons that pass freely between end and central cells. The electrons in turn transfer energy to the solenoid ions, which are cooler than the electrons. In this way, some of the neutral-beam power required to maintain the plugs is also used to heat the solenoid ions.

Because of the long confinement time of ions in the solenoid, the heat injected via the plugs goes a long way, sustaining a very large volume of plasma in the solenoid. The Q of this system is large because it is equal to the solenoid fusion power (which is proportional to the plasma volume in the solenoid) divided by the power of the neutral beams being injected into the plugs (the only external power input). Table 1 lists the parameter values for a tandem mirror reactor (TMR) that would have a system Q of 5, a fivefold improvement in Q compared to a conventional mirror reactor. Figure 3 shows an artist's conception of a TMR.

THE TMX

The purpose of the TMX is to provide a proof-of-principle evaluation of the tandem mirror concept as rapidly as possible. To do this, the experiment must

- Demonstrate the establishment and maintenance of a potential well between two mirror plasmas.
- Show that high- β , minimum- B mirror plasmas (the plug plasmas) can stabilize a high- β plasma in the straight solenoid (β is the ratio of plasma pressure to the pressure of the confining magnetic field).
- Investigate methods of enhancing the Q of the system by such means as lengthening ion confinement time in the plugs, maximizing the density of the plasma in the plugs, and minimizing the neutral-beam injection power required by the plugs.

As we design TMX, we are focusing on aspects that are unique to the tandem mirror configuration. By directly applying experience gained from the Baseball and 2X1B experiments, we increase con-

Table 1. Parameters for a conceptual tandem mirror reactor (TMR) with a system Q of 5 for the LLL tandem mirror experiment (TMX). Parameters of the TMX are roughly proportional to those of the TMR; the confinement mechanism is similar.

Parameter	TMR	TMX
Energy of neutral beams injected into the plug, keV	1200	40
Magnetic field in the plug, T	16	1.0
Ion density in the plug, particles/cm ³	8.5×10^{14}	5×10^{13}
Ion density in the solenoid, particles/cm ³	1.0×10^{14}	1.2×10^{13}
Electron temperature, keV	43	0.2
Potential barrier for electrons, keV	260	1.1
Temperature of solenoid ions, keV	30	0.08
Potential barrier for ions, keV	92	0.29
Ratio of ion confinement time to ion-ion collision time	100	140
Magnetic field in the solenoid, T	2	0.05
Ratio of plasma pressure in the solenoid to magnetic field pressure in the solenoid	0.7	0.5
Length of plasma in the solenoid, m	100	5.5
Ratio of plasma volume in the solenoid to that in the plugs	430	570

fidence in the reliability of TMX and shorten construction time. For example, we bring years of experience to the designs of both the end plugs and the injection system. The TMX plugs are nearly identical to the 2XIIIB machine; for forming the plug plasmas, we chose the neutral-beam injection system proven successful in 2XIIIB. There is a vigorous program under way at the Lawrence Berkeley and Livermore Laboratories to further develop neutral-beam and superconducting magnet technology; we know that a tandem mirror could operate in steady state using superconducting magnets, with continuous fueling and heating by neutral beams. The requirement for a high beta in the plugs has already been met by the 2XIIIB experiment.

Each plug has 12 injectors; of these, four inject 40-keV beams of neutral deuterium and eight inject 20-keV beams of neutral deuterium. Each injector delivers about 1 MW of power in a 25-ms pulse. The neutral-beam injectors and their power supplies constitute the highest-cost item for TMX. To reduce costs, 12 of the 20-keV injectors will be borrowed from 2XIIIB.

Eighteen coils are used on TMX (Fig. 4). Each plug consists of a baseball coil with the mirror fields augmented by two C-shaped coils located in the jaws of the baseball coil. Six large, ring-shaped coils create the solenoidal magnetic field. At each end of the solenoid, a pair of nested C-shaped coils followed by an octupole coil provide a transition from the fan-shaped field of the plug coil to the

Fig. 3. The tandem mirror reactor. Conceptual drawing of a fusion reactor shows (in cutaway) 100-m-long solenoid of red modules between two plugs with orange transition coils. Ribbed structures protruding radially from the plugs are neutral-beam injectors. Large, oval blue-gray tanks at the ends house direct converters to convert plasma losses and charged fusion energy directly into dc electricity to run the neutral beams. Fusion neutron energy is recovered and transferred to steam generators and turbines in the power house in back. The conical buildings are cooling towers.

Fig. 4. TMX magnet and neutral-beam injection system. Massive baseball-shaped coils in the ends create 2-T mirror fields for the plugs. Large ring-shaped coils form the central solenoid. C-shaped and octupole coils smooth the transition of field lines between the plugs and solenoid. Twelve neutral-beam injectors (1 MW each) power each plug.

cylindrical field of the solenoid. All coils are copper, water-cooled, and operated for a few seconds by dc power supplies. The dc power now available will limit the magnetic field strength of the two mirror systems to 2 T. Figure 5 shows the TMX machine as it will appear when complete.

Because the plugs were chosen to be of 2XIIB size, the overall scale of TMX is determined by the 1-m mirror-to-mirror length of each baseball coil. Adding a 5-m-long solenoid (for a high- Q tandem reactor the plasma volume of the solenoid must be large compared to that of the end plugs) and end tanks beyond the plugs to dispose of the plasma losses brings the total machine length to a little over 15 m.

The TMX is located in the area previously occupied by the Baseball experimental facility, which was shut down and removed to make room for TMX. Figure 6 shows the large pit under construction in which TMX will be placed; Fig. 7 shows the completed facility. Note that a 0.6-m-thick concrete wall will completely surround the experiment to shield personnel from the possibly large neutron fluxes produced by deuterium-deuterium fusion reactions.

By using existing facilities, borrowing neutral-

beam injectors from 2XIIB, and limiting power consumption to the available supply, we have kept the cost of the TMX to \$11.5 million, which is about half what the experiment would cost without these economies.

For TMX to provide the groundwork for a tandem mirror reactor, the characteristics of the TMX plasma must be as nearly in proportion to the corresponding reactor characteristics as possible, consistent with engineering, physical, and economic constraints on the experiment (see Table 1). Other than neutral-beam voltage and magnetic-field strength, the most severe constraint is the requirement that enough low-energy ions be lost through the ends of the solenoid to suppress microinstability in the plugs, just as a low-energy plasma stream from an external source is required to stabilize 2XIIB.⁵ Fortunately, the TMX plasmas not only meet these constraints but also have characteristics needed for a high- Q reactor:

- The confinement of solenoid ions in the TMX potential well should reach 100 ion-ion collision times.
- The volume of the solenoid plasma compared to that in the plugs is close to the volume ratio in a reactor.

Fig 5 Assembled view of TMX machine. Large end tanks are required to provide adequate pumping to dispose of plasma losses and gas emitted by the neutral-beam injectors. Plug magnets are inside the tanks. Total machine length is 14 m.

- The shape and stability of the TMX plasma are also very similar to those in a reactor.

FUTURE PLANS

If all goes well, the crucial physics issues—establishment of a potential well, determination of the stability of the solenoid plasma, and enhancement of plug confinement time—should be resolved by 1979–1980. This would be in time to decide what modifications should be made to the proposed LLL Mirror Fusion Test Facility (MFTF)⁶ as a next step in the development of the tandem mirror. Successful experiments on TMX, coupled with subsequent experiments in MFTF (scheduled to begin operation in 1981), should provide a sufficient basis for building an experimental power reactor (one that produces a small amount of net fusion-power) sometime in the 1980's.

Fig. 6. The TMX is located in the area previously occupied by the Baseball experimental facility. In May 1977, the construction site looked like this. Note the large, 16-m-long pit to house the TMX machine.

Fig. 7. Drawing of the TMX machine after completion. The finished facility will include a 0.6-m-thick concrete personnel shield.

NOTES AND REFERENCES

1. G. I. Dimov, V. V. Zakaidakov, and M. E. Kishinevsky, *Fizika Plazmy* 2, 557 (1976); also "Open Trap with Ambipolar Mirrors," in *Proc. 6th Inter. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Federal Republic of Germany, 1976* (IAEA, in preparation), Paper C4.
2. T. K. Fowler and B. G. Logan, *Comments on Plasma Physics and Controlled Fusion*, II, 167 (1977).
3. G. G. Kelley, "Elimination of Ambipolar Potential-Enhanced Loss in a Magnetic Trap," *Plasma Physics* 9, 503 (1967).
4. The LLL Magnetic Fusion Program and Q enhancement are discussed in detail in the June 1976 *Energy and Technology Review* (UCRL-S2000-76-6), pp. 1 and 10.
5. F. H. Coensgen, J. F. Clauser, D. L. Correll, W. F. Cummins, C. Gormezano, B. G. Logan, A. W. Molvik, W. E. Nexsen, T. C. Simonen, B. W. Stallard, and W. C. Turner, "2XIIIB Plasma Confinement Experiments," in *Proc. 6th Inter. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Federal Republic of Germany, 1976* (IAEA, in preparation), Paper CN-35/C1; see also the November 1975 issue of *Energy and Technology Review* (UCRL-S2000-75-11), p. 1.
6. MFTF (called MX in the article referenced) is described in the June 1976 *Energy and Technology Review* (UCRL-S2000-76-6), p. 1.

Key Words. magnetic mirrors; magnetic mirrors—design; mirror ion experiment; mirror machines; mirror machines—design; smas; tandem mirror experiment; TMX.

GEOTHERMAL ENERGY SYSTEMS

Taming Geothermal Brines For Electrical Power

Although vast sources of energy are tied up in the geothermal brine reservoirs of California's Imperial Valley, this energy cannot yet be efficiently recovered because of the massive precipitation of minerals from the brine. Precipitated solids form scale and fluid-suspended solids that can clog and erode the brine-handling machinery. The problems are most severe in the vital energy-conversion components where temperature and pressure drops are the greatest.

In parallel with engineering development of the total-flow process, we are currently investigating brine acidification as a means for controlling scale and solids precipitation. Studies are being conducted to select the component materials best suited for handling the acidified brine, and various methods are being investigated for efficient disposal of the spent brine.

As a result of recent technological developments, the vast sources of thermal energy that lie beneath the earth's surface may soon yield to commercial development. Throughout the world massive subterranean geothermal brine deposits are hot enough and close enough to the earth's surface to make their exploitation economically feasible. Just such a deposit is the Salton Sea Geothermal Field.

The Lawrence Livermore Laboratory has been working to help develop the Salton Sea Geothermal Field as an energy source since early 1974. This field was chosen for development because it is a large, high-temperature reservoir (about 300°C) located near large metropolitan areas, which have high energy needs. The potential energy available from the field has been estimated to be approximately 83 600 MW·yr of electricity, equivalent to the electrical energy production from 1 billion barrels of oil.

In addition to being very hot, the brine is also very salty and filled with minerals that can erode

Contact George E. Tardiff (Ext. 3946) for further information on this article.

and clog machinery. Dissolved solids run as high as 30% by weight in some areas of the deposit. Thus, the brine itself is the major obstacle to economic development of this thermal energy source.

As long as the brine is very hot and under pressure, the dissolved solids remain dissolved. To convert the thermal energy to electrical energy, however, the brine loses its heat and pressure while expanding. When the temperature and pressure drop, some of the water turns to steam, and the dissolved minerals come out of solution and precipitate as either deposited scale, suspended particulate solids, or suspended gel solids. Solids precipitation will occur everywhere in the brine-handling system, including the brine-transport plumbing, control components, and energy-extraction machinery. The problem is most serious in the energy-extraction machinery, since it is here that the temperature and pressure drop is most severe.

Scale deposits can clog the system, suspended solids can erode the system and plug up the pores of the underground disposal reservoir, and the hot pressurized brine solution can corrode nearly all materials that it touches. Clogging, erosion, and corrosion can all operate singly to cause equipment failure; they can also interact to accelerate the process. Erosion-assisted corrosion is an especially lethal combination with a high potential for inducing equipment failures. The resolution of these problems—the key to efficient and economical conversion of the geothermal energy from the Salton Sea Geothermal Field—comes down to two basic technological imperatives: develop a method to control solids precipitation, and select suitable erosion- and corrosion-resistant materials to survive the punishing environment.

THE GEOTHERMAL ENERGY DEVELOPMENT PROGRAM

Our brine chemistry and materials work¹ is part of the Laboratory's Geothermal Energy Development Program, whose general objective is to develop advanced technologies for water-dominated hydrothermal resources, with emphasis

on solving the problems of the high-temperature, high-salinity geological resources in California. Our basic tasks are to develop reliable, efficient energy-conversion systems, and to develop methods for controlling scale formation, handling and removing solids, and disposing of spent brine. All of these tasks depend on solving the problem of solids precipitation and materials erosion and corrosion.

The Total-Flow Turbine System. The Laboratory's development of an advanced energy conversion system is concentrated mainly on a total-flow impulse turbine system.² "Total flow" means that the energy-conversion unit (a specially designed turbine) is driven by the whole wellhead product: highly divided water droplets, vapor, dissolved solids, suspended solids (if any), and additives (which are discussed below). The term total flow is sometimes used interchangeably with "two phase," which refers specifically to the combined liquid and vapor states of the brine product. The term "separated brine" is applied to brine from which the vapor has been removed. Two-phase, or unseparated, brine is considered to be low quality if it has a low vapor fraction; quality is expressed as the percentage of vapor.

An impulse turbine is analogous to a paddle wheel, in which the torque is achieved by a moving mass impinging upon a peripheral deflection surface. For the impulse turbine, the mass flow is directed by specially designed nozzles.

The total-flow concept for geothermal brines appears to be more economically attractive than conventional hydrothermal energy-conversion techniques that extract and use only the vapor fraction, discarding the hot brine, which still contains about one-third of the total available energy. The goal of the advanced energy conversion project is to develop the total-flow geothermal energy system to help accelerate commercial development of this important resource.

Figure 1, a schematic of the total-flow turbine system, illustrates the problem areas requiring solutions by the brine chemistry and materials technology effort. In the total-flow turbine system, wellhead brine is expanded (flashed) through nozzles and its thermal energy converted into kinetic

Fig. 1. Simplified schematic of the total-flow impulse turbine system. Wellhead brine in both liquid and vapor states is expanded through nozzles to drive specially designed rotor blades. Steam and brine liquid are then separated: the steam is disposed of as water and vapor; the spent brine is returned to underground reservoirs. For simplicity, only one nozzle is shown.

energy as high-velocity jets of fluid and vapor. These jets drive an axial-flow impulse turbine that drives a turboalternator that generates the electricity. Field experiments during 1975 showed that the rate of scale deposition by wellhead brine in test nozzles was about 1 mm/day. Wear blades placed in the nozzle exhaust jet were severely eroded by suspended solids precipitated during brine expansion through the nozzles.

Of the possible methods for control of solids precipitation, only two hold promise for simultaneously controlling scale and suspended

solids: chemical modification of the brine to prevent precipitation, and pre-precipitation of the solid material by treating the brine at the wellhead and removing the solids before the brine enters the conversion system. The latter method was considered only as an alternative, because advanced technology and equipment would be needed to remove the solids from the high-temperature wellhead brine. Other methods of scale control based on prevention of scale accumulation would be less effective because they do not solve the problem of solids entering the turbine. Thus, we initiated a major effort

to identify and test methods for modifying brine to prevent the precipitation of scale and suspended solids.

Anticipating success with a scale- and solids-control method, we established a test program to select materials for the impulse turbine components. This effort was mainly focused on discovering those materials resistant to erosion and stress corrosion in the brine environment.

Industrial Support Program. Much of this work can be applied to various geothermal energy conversion concepts or systems, and the Laboratory has established an Industrial Support Program to provide technological assistance to industries that are trying to use the geothermal resources of the Salton Sea field. This program parallels the total-flow program. It provides technological assistance to the Geothermal Loop Experimental Facility, a joint venture of ERDA and the San Diego Gas and Electric Company. The purpose of the facility is to evaluate the feasibility of a flashed-steam-binary-cycle energy conversion system, a hybrid system that incorporates a sequential four-stage steam flash process. The steam is scrubbed in bubble-cap tray towers and then directed through heat exchangers, where the heat is transferred to a secondary working fluid. In the present operation, water is used as the working fluid and is expanded across a throttling valve to simulate the pressure drop across a turbine. The steam condensate can be either cascaded to the next stage, combined with the brine, or used for spray-pond water.

The decision on whether to proceed with a full-scale flash-binary demonstration plant is tentatively planned for 1979. The final decision to build this plant will be based on information from our brine chemistry and materials work. Specifically, we have been working to

- Characterize brine and steam flows.
- Measure production of precipitated solids.
- Characterize the physical and chemical nature of scale and suspended solids.
- Test the most promising brine-modification scheme for scale- and solids-control to determine its feasibility for operations use.
- Identify an effluent treatment and solids-

removal method to permit successful long-term injection of spent brine into subterranean reservoirs.

Field work for the brine chemistry and materials-related problems is conducted with a Laboratory mobile field station at the Geothermal Loop Experimental Facility site.

RESULTS OF BRINE CHEMISTRY IN TOTAL-FLOW SYSTEMS

Scale Control. The total dissolved solids content of brine in the Salton Sea Geothermal Field ranges from 10% to 30% by weight. The brines are slightly acidic (pH 5 to 6). Although most of the dissolved solids are mixtures of sodium, potassium, and calcium chlorides, trace constituents such as silicon, heavy metals (iron, lead, copper), and sulfur comprise most of the suspended solids and deposited scale.

The process of solids precipitation depends on brine pH, which in turn is determined principally by the amount and distribution of noncondensable gases, mainly ammonia and carbon dioxide. Brine pH at the wellhead is generally near 5.8, while the downwell pH is estimated to be about 4.3. The higher wellhead pH is due to decomposition of carbonic acid to carbon dioxide gas as the pressure is reduced during flashing of brine up the wellbore. The pH of brine streams at the Geothermal Loop Experimental Facility varies between 5 and 6 in all stages of flashing.

In the experimental facility, most of the carbon dioxide is vented after condensation of the steam in the first-stage heat exchanger. Significant quantities of ammonia are released as the brine is flashed through the second, third, and fourth stages. The pH of the first stage condensate is 6.3, but this increases to above 9 in the second, third, and fourth condensate streams due to dissolved ammonia. In separated brine cooled by expansion through nozzles, the pH ranges from 5.4 to 6.3. All pH values given in this article are measured at ambient temperature.

A typical scale deposit is shown in Fig. 2. This deposit formed during about two weeks of flow of cooled (about 100°C) brine, supersaturated with

Fig. 2. Typical scale deposit formed inside a pipe after flow of cooled, unmodified brine for two weeks. This example underscores the need to prevent deposition of solid precipitates.

scale-forming elements. Although there are wide differences in temperatures, types of scales, and flow environments at the experimental facility, the scaling rates are remarkably similar.

Figure 3 shows a polished section of scale formed during flow of separated brine at about 200°C. It consists of iron-rich amorphous silica and copper-iron sulfide. The proportion of metal sulfides is generally higher (greater than 50%) at higher deposition temperatures. Deposition at approximately 100°C produces softer scales, consisting mainly (more than 80%) of iron-rich amorphous silica. The high-temperature silica scale appears microscopically as 1- to 5-nm colloidal silica particles, aggregated as a porous gel network. This polymerization of dissolved monomeric silica to

Fig. 3. Polished cross section of scale deposit formed at 200°C during flow of separated brine. Darkest areas are epoxy mounting material. The porous silica colloids precipitate first, forming a host for the nucleation and deposition of the sulfides.

more complex polymers ultimately results in the production of colloidal particles. Aggregation of these colloidal particles forms the porous structures and provides a host for nucleation and further deposition of sulfides. In every deposit examined, a sulfide-deficient scale is found adjacent to the substrate.

We found that the concentration of suspended solids, collected by in-line filtering of brine, increases from 7 ppm at the production well (about 200°C) to up to 480 ppm at the injection wellhead (about 100°C). These solids are primarily lead sulfide-silica mixtures at higher temperatures and amorphous silica at lower temperatures.

We studied the solution chemistry of silica and analyzed the chemistry of sulfide precipitation to es-

tablish a method for controlling scale and the precipitation of suspended solids. Figure 4 illustrates how pH reduction lowers the rate at which silica is polymerized (Fig. 4a) and slows the kinetics of colloidal silica aggregation that would lead to the formation of scale (Fig. 4b). An analysis of the chemistry of metal sulfide precipitation in chloride solution suggested that sulfide precipitation could also be suppressed by acidification. Brine acidification shows promise as a method for reducing or preventing the deposition of scale and the precipitation of suspended solids. Reduction of the pH to below 4 reduces precipitation of solids by more than 50 times.

The Laboratory's mobile field station was designed specifically to test acidification as a means to control the precipitation brine solids and to select materials resistant to the erosion and corrosion effects of acidified brine.

Test nozzles were used to expand wellhead brine

from about 1969 kPa and 220°C to about 103 kPa (atmospheric pressure) and 100°C. The brine and vapor from the wellhead were first separated. For the initial brine acidification tests, hydrochloric acid was injected into the separated brine prior to its introduction into the nozzle.

The unmodified, low-quality separated brine was introduced into the nozzle inlet. Expansion of the brine caused enough scaling to reduce the 0.25-in. nozzle diameter by 19% after 24 hr. Acidification to pH 4.5 or less eliminated such scale deposition. Figure 5 clearly demonstrates the effect of acidifying brine on scaling in a Teflon nozzle. Similar results were obtained with other nozzles made from the commonly used titanium alloy Ti-6Al-4V.

More recently, we have found that scale deposition on nozzles is also prevented in the expansion of two-phase 11%-quality brine, acidified prior to expansion. A diagram of the two-phase test apparatus is shown in Fig. 6. Here, the brine and vapor are

Fig. 4. These curves demonstrate that pH reduction reduces the rate at which silica is polymerized and slows the kinetics of colloidal silica aggregation that would lead to the formation of scale and suspended solids. (a) Rate of polymerization of silica acid in various acidic solutions, and (b) stability of silica sol at various pH values.

Fig. 5. Teflon nozzles showing the effect of brine acidification on scaling after 20 hr of flow exposure. Brine entered the nozzle inlets at 220°C and exited at 100°C (flow direction in this photo is from bottom to top). The nozzle on the right shows scale deposits resulting from the flow of natural brine. The lack of scale on the left nozzle is evidence for the reduction of scaling rate by acidification of brine to pH 4.5 or less. These tests closely approximate the total-flow turbine nozzles.

separated, the acid is introduced into the brine, and the vapor and brine are recombined prior to expansion. For these tests, separator temperatures and pressures were stabilized between 192 and 196°C and between 1960 and 2030 kPa, respectively.

We determined the quantity of acid required to control scale and solids precipitation by directly measuring acid and brine flows. The results show that the amount of hydrochloric acid required to acceptably reduce pH is about 120 ppm for separated brine and about 150 ppm for two-phase brine at 11% quality. The greater amount of hydrochloric acid is required in the two-phase brine because of the neutralization by ammonia. Acidification at these rates would increase plant operating costs by less than \$0.002/45 kg of brine processed. Assuming that 45 kg of brine is required to produce 1 kW·hr and that the cost of electricity at the bus bar is \$0.020/kW·hr, we estimate that adding this much acid to the brine would add less than 10% to the cost of energy.

Evaluation of Materials. Titanium-base alloys are currently the best materials for total-flow turbine systems, because they have a high strength-to-density ratio and are relatively resistant to stress-corrosion cracking in aqueous media.

We tested material erosion by placing wear blades that simulate turbine blades in the exhaust jet of brine expansion nozzles. Wear blades of Ti-6Al-4V alloy were exposed to two-phase, acidified brine for 60 hr. For these tests, profilometer traces of wear-blade leading edges were made on the blades as machined, after exposure to brine, and after removal of scale. The maximum depth of erosion is about 19 μm for carbonitrided and uncoated Ti-6Al-4V blades. A linear extrapolation of this figure yields about 2.8 mm of erosion for 1 yr of exposure, which is acceptable for a first-generation turbine system test. Furthermore, the titanium alloy showed no sign of stress-corrosion cracking at realistic turbine operating stresses. In similar tests, cobalt- and iron-base alloys failed.

Short lengths of 0.75-in.-diam zirconium tubing have been used to mix 4 *N* hydrochloric acid with separated brine and to carry the acidified brine to the nozzles. These tubes have been free of scale or degradation after several hundred hours of use. Since the total amount of material required for these tubes and nozzles will be small, the use of such an expensive corrosion-resistant material in upstream components of the total-flow system (where the brine is acidic and hot—in excess of 200°C) would not add significantly to the overall cost of a power-conversion plant. The total-flow system is particularly well suited to acidification for control of scale and solids precipitation, since all of the temperature drops occur in the nozzles. Downstream components (turbine case, separators, piping, and the injection casing) need only be resistant to acidified brine at the low temperature of nozzle exhaust (about 60°C). Downstream neutralization by dissolved ammonia will reduce corrosion there.

Preliminary electrochemical measurements of corrosion rates have assessed the potential of low chromium-molybdenum alloy steels for injection-well casings and components downstream from the turbines. At temperatures near 100°C small addi-

Fig. 6. Schematic of two-phase nozzle inlet test station. Before entering the system, the brine is separated into vapor and liquid. Acid is mixed with the brine liquid, which is then mixed with the vapor prior to expansion in the nozzle. The elbow simulates the turbine blade. Acidification of the brine in these two-phase flow studies reduced the rate of scale deposition.

tions of chromium and molybdenum can reduce the corrosion rate nearly tenfold relative to carbon steel to rates well within acceptable limits.

Disposal of Spent Brine. Injection of spent brine underground is the only acceptable means of disposal of the enormous quantities of brine required to operate even a small power plant. Brine acidification reduces the content of suspended particulate matter in the cooled effluent; thus, at first the acidified effluent should flow freely into the injection reservoir without plugging. However, acidification only delays silica precipitation, and successful injection is required for many years. We are evaluating how well acidified effluents can be injected by flowing the fluid through beds (mainly sandstone) that simulate the porous underground reservoir rock. Comparisons of permeability changes will be used as a basis for selecting the op-

timum fluid properties of the effluents for long-term injection.

BRINE CHEMISTRY FOR BRINE FLASHING SYSTEMS

Although the acidification process was developed initially for the total-flow impulse turbine system, it is now being evaluated for control of scale and solids in brine flashing systems, such as are used by the Geothermal Loop Experimental Facility. In the brine flashing process, the cooling of normal brine creates a solids-laden effluent, not suited for disposal by injection. The primary purpose of these tests is to determine if acidification of the working brine can lead to successful injection of the spent brine.

Besides acidification of the brine, another possible solution to the injection problem is to remove precipitated solids prior to injection. Various methods of solids removal from effluents are being investigated in small-scale tests—primarily methods of gravity settling and filtration for final clarification of the fluid. We are also investigating alternative and auxiliary methods for settling based on contact removal, that is, the tendency of solid particles to stick to surfaces, which results in a reduction of solids concentration. We are investigating such contact-removal devices as sand beds and devices designed to expose a high surface area of steel to the brine flow.

To carry out these effluent treatment and solids removal tests, a Brine Effluent Test Station is being constructed and will use the Geothermal Loop Experimental Facility's spent brine at the injection wellhead.

However, before brine acidification can be used to control scaling and solids in high-temperature brine flashing systems, we must first solve the problem of corrosion. Corrosion increases directly with increasing temperature; for example, for each 100°C rise in temperature, the corrosion of carbon steel in high-chloride brines increases tenfold. Carbon steel corrodes about 2.5 mm/yr in 100°C acidified brine but at a rate of about 24 mm/yr in 200°C acidified brine. Certainly, then, carbon steels or other low-alloy steels are not suited for use in a high-temperature brine flashing system.

Lining the high-temperature carbon steel components with corrosion-resistant materials is one solution to this problem. We have listed a wide variety of alloys and found the best to have a corrosion rate of 0.0015 mm/yr—promising as liners for brine flashing equipment. We plan to test lining material alloys to evaluate their resistance to general corrosion, stress-corrosion cracking, pitting corrosion, and weld corrosion. Cost analyses of plant construction are being made in parallel with the corrosion evaluations to determine the most economical materials for brine flashing systems.

A full-scale system test of brine acidification for scale control in the Geothermal Loop Experimental Facility is planned for late 1978. We are now

performing preliminary tests of acidification for the experimental facility using a scaled-down model of the facility at our field test station. Our initial objectives are to determine the maximum level of scale and solids control possible by acidification, consistent with maintaining corrosion rates below a level for which long-term operation of the experimental facility is feasible.

Several techniques are being investigated as means of reducing corrosion rates. One method we are currently evaluating is preprecipitation of scale prior to acidification. Preliminary results suggest that corrosion rates might be reduced fivefold by preplating a very thin layer of scale on all the internal brine-handling components. For long-term operation (up to 18 months) of the experimental facility, general corrosion rates will need to be kept below 0.15 mm/month.

CONCLUSION

Extracting energy from high-salinity, geothermal brines now appears feasible. Brine acidification promises to be an economical method for controlling scale and solids for both conventional and advanced energy conversion systems. To date, we have tentatively demonstrated economically viable solutions for scale accumulation and corrosion in the total flow system. We have also found materials for the brine-handling components that can withstand the corrosive fluids. We think we have found possible solutions for spent brine reinjection, and we are investigating a wide variety of promising solutions for scaling and corrosion in high-temperature brine flashing systems.

Key Words: acidification; brines—corrosion; geothermal brines; geothermal brines—scaling effects; geothermal energy—energy conversion; Salton Sea area.

NOTES AND REFERENCES

1. Previous geothermal brine studies, with special reference to our work on controlling scaling and corrosion, are discussed in the March 1976 *Energy and Technology Review* (UCRL-52000-76-3), p. 1.
2. Development of the total-flow impulse turbine and an auxiliary reaction turbine are discussed in the May 1977 *Energy and Technology Review* (UCRL-52000-77-5), p. 7. (Also in this issue is an overview of the Laboratory's geothermal energy development efforts, p. 1.)

ENVIRONMENT AND SAFETY

Flow Cytometry in Cervical Cancer Diagnosis

Early detection of malignancies has, for the last 25 years, been based mainly on microscopic examination of cells taken from the anatomical site under suspicion. The Pap smear, the analysis of surface cells that can be easily scraped off the cervix, has been established as an effective technique for early detection of cervical cancer. Such cytological screening for cancers of the lung, bladder, bowel, breast, and prostate appears to be technically possible but is prohibitively expensive. We are conducting research to automate the diagnosis of cervical cancer with the goal of extending this technique to other cancers. Using the LLL multiparameter flow cytometer and cell sorter, we have been able to sort out abnormal cells based on their DNA content and cell size. However, normal cells also occur in the sorted sample, so we are searching for a third parameter to decrease their num-

ber. With this improvement, multiparameter flow cytometry will be ready for a field trial in the clinical diagnosis of cervical carcinoma.

Over 90% of lung, bladder, bowel, breast, and prostate cancers occur in people over age 45. Massive screenings of this population and other populations at risk (such as cigarette smokers) are desirable because cancers are all potentially treatable if caught early. In general, the earlier the diagnosis, the better the prognosis. This is true because cells appear to follow a standard pattern in becoming cancerous. Normal cells first become dysplastic, which means they have slightly abnormal nuclei. In time, these cells become carcinoma *in situ*, localized cancer, which eventually change to invasive cancer. This cancer invades nearby tissues and can spread throughout the body. Patients respond well, however, if they are treated before the cancer begins to spread.

Contact Ronald H. Jensen (Ext. 35651) for further information on this article.

The development of the Pap smear, a cytologic screening technique, has resulted in detection of cells in these earlier stages and in a 50% reduction in deaths due to cervical cancer. The Pap smear, obtained by many women every year, is the only cytological screening routinely employed at present. It is taken by a physician or nurse, mounted on a microscope slide, and stained for microscopic analysis. A trained cytotechnician analyzes the stained cells for deviations typically found in dysplastic or cancerous cells: in nuclear size and shape, cell size and shape, and staining variability both in intensity and color. This tedious and time-consuming task is now done for cervical screening, but it would be increasingly burdensome if it were extended to other cancers as well.

Automation is a possible approach to the examination of such a large number of cytology specimens. It could be a diagnostic technique or a prescreening tool to eliminate the large number of normal samples from further detailed cytological screening. This could eliminate as much as 90% of manual screening. To encourage research in automating diagnostic cytology, the National Cancer Institute has established a Committee on Cytology Automation, which administers a program to determine the efficacy of automated cytological diagnosis of human cancer. Our laboratory has been a part of that effort since 1974 under an agreement between the National Cancer Institute and ERDA.

We chose to work on automating the diagnosis of cervical cancer for several reasons. First, as described above, diagnosis by microscopic examination is very effective and can be used as a measuring stick to determine how well the automated techniques can diagnose. Second, a continuous supply of cell samples is available to us from the Dysplasia Clinic at the University of California at San Francisco. Finally, the automated analyses are based on deviations in normal cellular properties that we expect to be similar for many different types of cancer.

Our approach is based on the use of a multiparameter flow cytometer as the primary screening instrument. Such an instrument has been used for about 10 years, but primarily as a research tool, not

a clinical instrument. The design of the LLL flow cytometer¹ and some research applications² have been described previously. For flow cytometry, large molecules (for example, DNA or enzymes) in intact cells are stained with fluorescent probes. The stained cells in suspension are made to flow in a very narrow stream so that the cells travel in single file across a beam of intense blue laser light, which excites the dye to fluoresce. The fluorescent flash from each cell is picked up by an optical system and converted to an electrical pulse, which is integrated, amplified, digitized, and stored in the memory of a multichannel analyzer. Fluorescence from several probes can be simultaneously measured for each cell. In only a few minutes, signals from about 100 000 cells are stored in the multichannel analyzer, enough to obtain good statistical precision. The contents of the analyzer memory can be displayed directly as a histogram depicting the frequency of cells with equivalent intensities of fluorescence. Alternately, the contents of the memory can be transmitted directly to an online digital computer for further processing and analysis.

TWO CELL MARKERS

The successful application of flow cytometry to the automated diagnosis of cervical cancer rests on selecting diagnostic markers that occur in detectably different amounts in cancerous cells than in normal cells. We selected DNA content as our diagnostic marker because it is the most quantitative cytochemical property of mammalian cells, it has been extensively studied, and it is known to be frequently abnormal in cancer cells.³

Chromomycin A₃ and its close analog, mithramycin, are fluorescent stains that bind DNA in solution.⁴ Since they stain only double-stranded DNA (which occurs in cell nuclei), they are good candidates as probes for cellular DNA content in gynecological specimens. We developed procedures for staining cervical cells with chromomycin A₃⁵ from the original cell staining studies for mithramycin.⁶ We used microfluorophotometric analysis of cells mounted on microscope slides to

measure single-cell fluorescence intensities and to measure nuclear-to-whole-cell fluorescence ratios. Bright yellow fluorescence specific to cell nuclei could be obtained over a wide range of conditions, providing that pH was above 6, that magnesium ions were present, and that the chromomycin A₃ concentration was above 10⁻⁶ M. Figure 1 shows both the phase image and the fluorescence image of a microscope field containing several chromomycin A₃-stained cervical cells, and it illustrates the bright, nuclear-specific fluorescence that we can obtain.

After about a year of research, we developed a standard staining method that allowed us to analyze the samples, first by exciting the stain with 458-nm light from the argon laser in our flow cytometer and then by measuring fluorescence by single- or multiple-parameter flow cytometry.

Cell size is also a marker for dysplasia, carcinoma *in situ*, and invasive carcinoma. Although abnormal

cells vary considerably in size, they tend to be intermediate compared to all the cells that occur normally in gynecological samples. Since the intensity of 90° light scatter increases with the size of the cell, this parameter can help us discriminate between normal and abnormal cells.

TWO-PARAMETER FLOW CYTOMETRY

We used two-parameter flow cytometry to analyze about 300 gynecological samples, 100 of which contained abnormal cells. Using chromomycin-A₃ fluorescence intensity as a measure of cellular DNA content and 90° light-scatter intensity as a measure of cell size, we obtained histograms that describe the cell types in each gynecological sample. We can generate an isometric view of such a histogram (Fig. 2) by measuring chromomycin-A₃ fluorescence intensity and 90° light-scatter intensity simultaneously on each cell.

Fig. 1. Micrographs of chromomycin A₃-stained cervical cells—three large epithelial cells and one small white blood cell. Both photographs are of the same microscope field; (left) phase illumination, (right) fluorescent image.

Fig. 2. Histogram of exfoliated human cervical vaginal cells measured by flow cytometry. Two properties of each cell were measured simultaneously: height above the plane shows frequency of occurrence, location on the plane reflects cell size and DNA content. The surface features generated by specific cell types are reproducible and can be diagnostic. Precancerous and cancerous cells are concentrated in the abnormal region and can be sorted for microscopic analysis.

On the histogram, the height above the plane shows frequency of occurrence, and the location on the plane shows DNA content and cell size. Note that both the fluorescence and scatter signals were converted to logarithms before they were digitized, and a signal twice as intense as another signal is separated from it by seven channels.

We used a flow sorter to identify the cell types responsible for particular surface features in the two-parameter histogram. Flow sorters use the same principles of measurement as do flow cytometers, but they separate cells whose fluorescence and light scatter fall within a predeter-

mined range of values.⁷ In the LLL sorters, the stream carrying the cells breaks up into uniform droplets after the fluorescence measurement. The droplets can be charged positively or negatively or left uncharged, depending on whether or not the measurement of fluorescence and light scatter falls within a preset range. As the droplets fall through a 1000-V field, they are deflected according to their charge and thus enter separate containers.

We have sorted the cells responsible for each feature in the two-parameter histograms and identified the cell types microscopically with a standard Pap stain.⁷ Cells were sorted from the region of

normal fluorescence intensity (channels 15 to 30) and intervals of increasing light scatter intensity, and the sorted cells were categorized. The percentage of each cell type in each sorted fraction (Fig. 3) reveals that the peak at low scatter intensity is due to leukocytes (white blood cells). The ridge at the same fluorescence intensity but increased light scatter intensity is due to normal, mononucleate epithelial (surface) cells. The saddle between these peaks is a region where transformation-zone cells give signals. Transformation-zone cells are normal cells that grow at the anatomical site where most cervical cancers begin. Their presence in a sample is a sign that the specimen was obtained from the correct region for an accurate diagnosis. Thus, signals that appear in the saddle between the two normal cell peaks indicate an adequate specimen, but the cells are perfectly normal and expected in benign samples.

Signals from abnormal cells (dysplastic, localized cancer, or invasive cancer) invariably appear at

fluorescence intensities greater than channel 28 (see Table 1). Abnormal cells comprised from 17 to 34% of the cells sorted from abnormal specimens with the sorting window set for fluorescence channels 28 to 35 and scatter channels 16 to 29. This represents an average enrichment of fourteenfold times over the 2% average frequency of abnormal cells in the samples prior to sorting. Thus, a large fraction of the abnormal cells display fluorescence and scatter intensities in the sorting window, and relatively few benign cells display similar intensities.

AUTOMATED DIAGNOSIS IS NOT YET POSSIBLE

The objective in applying flow cytometry to clinical diagnosis is to detect dysplastic, carcinoma *in situ*, or invasive carcinoma samples based on characteristic features in their histograms. The two-parameter region that is richest in diagnostic information (approximately channels 30 to 40 in log-fluorescence and channels 20 to 30 in log-90° light

Fig. 3. Frequency of cell types sorted from normal fluorescence region. A normal gynecological specimen was chromomycin A₃-stained and sorted based on log-fluorescence channels 15 to 30 and three intervals of log-90° scatter. The sorted cells were restained and identified cytomorphologically. The frequency of each cell type is indicated by "Prewflow" for the original sample and by brackets for each sorted fraction. The strong correlation between cytomorphology and 90°-light-scattering intervals supports the usefulness of this means of identifying cells.

scatter) contains signals from abnormal cells at 14 times the frequency of the sample as a whole. Yet, even though only a small fraction of the normal cells in a gynecological sample cause signals to appear in that same region, a large percentage of all the signals in the region are caused by normal cells. The cell types that have been identified in fractions

sorted from the high fluorescence region are listed in Table 2. These represent a large spectrum of the cell types found in gynecological specimens. Many of the signals at high fluorescence are caused by aggregates of normal cells or by binucleate normal cells. These would appear to the flow analyzer to be similar to dysplastic, localized cancer, or invasive

Table 1. Frequency of abnormal cells in fractions sorted from regions of high fluorescence intensity.^a

Cytomorphologic sample diagnosis	Original specimen	Percentage of abnormal cells		
		Sorted fractions by channels		
		5 to 15	16 to 29	30 to 50
Mild dysplasia	2.8	0	23.4	17.6
Moderate dysplasia	1.4	0.2	34.4	7.2
Moderate dysplasia	2.8	0.4	24.0	16.6
Severe dysplasia	2.4	0.2	32.8	4.0
Severe dysplasia	1.4	0	17.4	2.8

^aChromomycin A₃-stained cells were sorted from abnormal samples based on log-fluorescence intensity channels 28 to 35 and three intervals of log-90° light scatter intensity. Cells were restained for cytomorphological analysis and categorized as normal or precancerous. The cytomorphologic diagnoses showed that none of the samples was cancerous, but they all contained abnormal, precancerous cells.

Table 2. Cell types in fractions sorted from regions of high fluorescence intensity.^a

Cell type	Diagnostic category	Percentage of cells in fraction by channel		
		5 to 15	16 to 28	29 to 50
Dysplastic	Abnormal – precancerous	0.2	34.4	7.2
Leukocytes	Inflammatory – white blood cells	97.8	20.3	15.0
Transformation-zone	Normal	1.0	19.7	3.8
Epithelial	Normal – surface cells	0	14.4	63.8
Epithelial and leukocytes	Normal – cell aggregates	1.0	11.1	11.3
	Total	100.0	100.0	100.0
Fraction of total sample sorted from interval		0.9	2.0	13.1

^aChromomycin A₃-stained cells were sorted based on log-fluorescence intensity channels 30 to 35 and three intervals of log-90° light scatter intensity. Cells were restained for cytomorphological analysis and categorized according to cell type.

cancer cells—moderate in size with high DNA content.

To increase the potential accuracy of automated cytological diagnosis, we are searching for new, independent markers that are correlated with dysplasia, carcinoma *in situ*, and invasive carcinoma. The most promising of these markers is the plasminogen-activator enzyme. Our present research is directed toward obtaining a fluorescent cytochemical probe that reveals the cellular level of this enzyme. By adding a third parameter relating the plasminogen-activator level to the present two parameters, multiparameter flow cytometry should be ready for a field trial in actual clinical diagnosis of cervical carcinoma.

LOOKING AHEAD

Success in automating the cytologic diagnosis of cervical cancer may lead to several further benefits. The cytochemical and instrumental advances can be applied toward diagnosis of other cancers for which cell samples can be obtained (i.e., lung, bladder, or prostate). The staining reactions and cytochemical insights obtained may also lead to a better understanding of the molecular events involved in the transformation of normal, healthy tissue to malignant, life-threatening tissue. Such understanding would not only be medically beneficial, but would also be of significant benefit in understanding the processes of mammalian cell growth, development, and control.

Key Words: cancer; carcinomas; cells; flow cytometry.

NOTES AND REFERENCES

1. M. Van Dilla, L. Steinmetz, D. Davis, R. Calvert, and J. Gray, *IEEE Trans. Nucl. Sci.* NS-21, 714 (1974).
2. J. Gray, A. Carrano, D. Moore II, L. Steinmetz, J. Minkler, B. Mayall, M. Mendelsohn, and M. Van Dilla, *Clin. Chem.* 21, 1258 (1975); M. Van Dilla, B. Gledhill, S. Lake, P. Dean, J. Gray, V. Kachel, B. Barlogie, and W. Gühde, *J. Histochem. Cytochem.* 25, 763 (1977).
3. N. Böhm and E. Sprenger, *Histochemie* 16, 100 (1968); T. Caspersson, G. Lomakka, and O. Caspersson, *Biochem. Pharmacol.* 4, 113 (1960); A. Zetterberg and P. Espositi, *Acta Cytologica* 20, 46 (1976).
4. R. Nayak, M. Sirsi, and S. Podder, *Biochem. Biophys. Acta* 378, 195 (1975).
5. R. Jensen, *J. Histochem. Cytochem.* 25, 573 (1977).
6. H. Crissman, M. Oka, and J. Steinkamp, *J. Histochem. Cytochem.* 24, 64 (1976).
7. D. Barrett, F. King, R. Jensen, and J. Merrill, *Acta Cytologica* (in press).

PHYSICAL SCIENCES AND ENGINEERING

Probing Nuclei With LLL's Electron Linear Accelerator

Linear accelerators help expand our understanding of basic nuclear phenomena. This understanding yields many benefits: we can use it to design superior nuclear weapons or to improve our knowledge of materials for nuclear reactors. We use the LLL 100-MeV electron linear accelerator—linac—for a variety of applications, such as measuring neutron cross sections, producing gamma rays to make radioactive isotopes, and generating positrons for photonuclear experiments.

The LLL electron linear accelerator—one of our basic tools for studying the atom's nucleus—accelerates primary beams of electrons up to energies of 100 MeV. The electron beams are then directed onto one of several kinds of production targets to generate secondary beams of neutrons, high-energy gamma rays, or positrons.

Our 100-MeV linac is a source of abundant neutrons that simultaneously covers ten orders of

magnitude of neutron energy (from 10^{-3} to 10^7 eV). This feature is especially important to those LLL programs that depend on a knowledge of neutron cross sections. Other types of neutron sources produce more intense beams in narrower energy regions; for example, the Rotating Target Neutron Source produces neutrons in a narrow energy range near 14 MeV. However, a linac has the significant advantage of making simultaneous measurements over a broad neutron energy range at a single facility.

LLL's 100-MeV electron linac belongs to a class of accelerators that ranges from small medical and radiographic machines (with a few-MeV energy limit) to the 2-mile-long giant at the Stanford Linear Accelerator Center (with an energy capability of 20 000 MeV). The energy range chosen for a research accelerator mainly depends on the characteristic energies of the phenomena studied. Thus, machines designed for subnuclear particles (such as Stanford's linac) need energies in the low thousands of MeV. In contrast, machines that search the nucleus (such as LLL's linac) use secondary beam energies up to about 50 MeV.

While ultrahigh energies are not needed for most

Contact John B. Czirre (Ext. 7226) for further information on this article.

Fig. 1. The Livermore electron linac. Compacted gravel, 3.7 m thick, shields the aboveground area from the linac's radiation. A thick concrete block wall isolates the accelerator cave on the right from the experimental caves. In these experimental caves, secondary beams of gamma rays or neutrons are produced. A removable converter can be placed at the output end of the accelerator to produce positively charged electrons (positrons), which in turn produce gamma rays in the experimental caves. Beam transport systems carry the electrons to any of the five neutron- and gamma-ray production areas (four underground, one aboveground).

nuclear experiments, we do need high beam power. Our linac reaches instantaneous levels of nearly 1000 MW in the short beam bursts of some experiments. Its average beam power is 10 kW under these conditions.

During the 25-plus years of electron linac existence, experimenters in many laboratories have applied these machines in research stressing the interaction of *electrons* with nuclei. However, at LLL we have used secondary beams rather than such primary beams. With our present linac, as well as with its smaller (40-MeV) predecessor, we have mainly focused on the interactions of neutrons and gamma rays with a wide range of nuclei. Our linac's primary electron beam serves merely as a convenient energy source to produce these secondary beams.

LINAC OPERATION

We placed our linac about 8 m below ground (Fig. 1) to contain the intense radiation from the secondary beams. An elaborate system of controls and interlocks further protects workers from accidental radiation exposure.

The electrons to be accelerated originate from the hot cathode of a pulsed electron gun (Fig. 2). The pulse duration can be varied from a few nanoseconds to a few microseconds, depending on experimental requirements. Our 14-m-long linac accelerates the electrons to full energy in seven stages.

Stage one occurs in the gun, where a high-voltage supply accelerates the electrons to an energy of 0.1 MeV. Electric and magnetic fields subsequently focus the electrons in a buncher cavity. This second-stage system breaks the beam up into millimetre-

Fig. 2. Schematic of the linac system. Electron acceleration begins in the gun on the far right of the accelerator cave. In the bunching system, faster electrons catch up with slower ones to produce successions of electron bunches. Each of the succeeding waveguide sections further accelerates the electron bunches. Klystrons, amplifiers that operate in the microwave region, are housed above each waveguide to provide the microwave power to boost the electromagnetic waves traveling the length of the accelerator. The electrons lock on to these waves, which are moving at almost the speed of light. At the output end of the accelerator, the transport system brings the particles to the bending magnets (not shown). From here, a primary beam of electrons, or a secondary beam of positrons from a positron converter, can be sent to the neutron- or gamma-ray-production areas.

long bunches by rejecting out-of-phase electrons and then accelerates the electrons to a velocity of 0.985 c (where c is the speed of light) at departure.

The beam is further accelerated by the electromagnetic waves in the five main linac sections. Each of these sections is a 2.3-m-long copper waveguide operating at a microwave frequency of 2855 MHz. Klystrons, housed above each accelerating waveguide, supply the necessary microwave power, which can be adjusted to control the energy gain of the electrons. In the waveguides, the advancing electromagnetic wavefronts accelerate the electrons. The electrons, which enter the first waveguide at 0.985 c , leave the final section at 0.99999 c and with an energy of about 100 MeV.

After the electrons leave the waveguides, one of two sequences may occur. The primary electron beam can be guided straight into a room containing a neutron-production target, bent 28° to the left to a second neutron-production target (both below ground), or bent vertically into a neutron-target silo for aboveground experiments. Experimental sites can be located in any of nine neutron flight paths coming from the target production areas. These beam tubes, ranging in length from 3 to 250 m, are used to provide energy selection by time-of-flight dispersion of the neutrons.

Alternatively, the electron beam may be intercepted by a target of material with a high atomic number, such as tungsten or tantalum, which

produces positrons. The positron beam can be routed into one of two experimental caves containing gamma-ray-production targets for experiments on photonuclear reactions—interactions of photons with nuclei.

NEUTRON PRODUCTION

For neutron experiments, we typically operate the linac in a mode that produces a primary electron beam with an energy of 100 MeV. This beam comprises 1440 pulses per second of electrons, each with a pulsewidth of 10 ns. Magnetic fields guide the primary electrons to water-cooled production targets of tantalum, which convert most of the electron energy to high-energy gamma rays. We optimize the target thickness so that a large fraction of these gamma rays interacts within the same target and produce neutrons from the nuclei. Collimators then restrict the neutrons within a narrow, parallel beam along one of the nine evacuated pipes, which lead to more than fifteen experimental stations below and above the ground.

Our linac produces a neutron beam with a continuous energy distribution, or a "white" spectrum of neutrons. All the neutrons are produced within a very brief period, coincident with the electron pulse incident on the production target. Because of the velocity distribution of the neutrons produced, such a narrow pulse allows us to use time-of-flight

techniques to accurately obtain neutron energies.

Reliable neutron-induced cross sections are essential to a number of LLL programs, both in weapons and nonweapons applications. As well, the rates at which breeder reactors produce fissionable uranium or plutonium isotopes depend on these cross sections. Many cross sections, if known at all, have large experimental uncertainties, and a better definition of them would help us solve a number of practical problems. With our linac, we conduct numerous cross-section measurements that yield basic data for solutions of a variety of problems.

Fission Cross Sections. We have used time-of-flight techniques to perform neutron fission cross-section measurements on various nuclei. In particular, we have measured the neutron-induced fission cross sections of uranium-235 to an accuracy of 2% for neutron energies of 0.8 through 14 MeV. Figure 3 illustrates the data obtained during a single linac experiment.

The uranium-235 nucleus is especially important because it serves as the main fissionable element in many reactors and weapons systems and as a standard element for obtaining other fission cross sections. It is in this latter application that we measured the fission cross sections of a variety of uranium, plutonium, americium, and thorium isotopes relative to the fission cross section of uranium-235. Flight paths ranged from 15 to 34 m. Figure 4 shows the fission cross-section ratio of plutonium-239 to uranium-235. Using two similar detectors (one each for plutonium and uranium), we measured the ratio of the fission rates at a given energy. Since we had already measured the fission cross section of uranium-235, we could deduce the plutonium cross section from this ratio. This method was also used for the other isotopes mentioned above.

Fission cross sections of many of the transplutonic nuclides are extremely difficult to measure: the isotopes are scarce, and samples are often too small to be measured using conventional techniques. Using the 3-m linac flight tube, in which the neutron flux is the highest, we recently applied a special, highly sensitive technique to measure the cross section of a 3- μ g sample of curium-245—a

Fig. 3 Fission cross section of uranium-235 as a function of neutron energy. This measurement gives us the probability of fission reactions occurring over a given range of neutron energies. All the data points shown were obtained during a single linac experiment. The experiment conducted on time-of-flight paths 60 m long spanned the energy range 0.8 to 14 MeV with an accuracy of 2%.

Fig. 4 Fission cross-section ratio of plutonium-239 to uranium-235. Using two similar detectors (one for plutonium, the other for uranium), we measured the ratio of fission rates at a given energy. Since we already knew the fission cross section of the uranium, with the above ratio we could deduce the plutonium cross section. The solid line depicts the previous estimate of the ratio.

sample over 1000 times smaller than those used to measure the more common fissile elements.¹ Our measurements yielded new results in the neutron energy range between 0.01 eV and 35 eV.

Currently we are measuring the fission cross section of another transplutonic element, americium-242m. Its nucleus has an unusually high thermal fission cross section (7×10^{-25} m²). We are using a specially designed hemispherical ionization chamber to detect fission fragments in the presence of copious alpha particles from the decay of the curium-242 daughter of americium-242m. Without the use of the special ionization chamber, these alphas would obscure the measurements of the fission fragments. The fission cross-section measurements will cover a wide range of incident neutron energies—from 0.01 eV through 20 MeV.

For americium-242m, we are also measuring the number of neutrons emitted per fission as a function of incident neutron energy, $\bar{\nu}(E_n)$. These measurements cover the energy range from 100 keV through 20 MeV. The ratio of $\bar{\nu}$ for americium-242m to $\bar{\nu}$ for uranium-235 is about 1.35. We measure $\bar{\nu}$ by requiring coincidence between a fission fragment detected in the ionization chamber and a neutron detected in a proton-recoil counter.

Neutron-Capture Cross Section. In conjunction with our neutron time-of-flight techniques, we have used several means of detecting the gamma rays resulting from radiative-neutron capture. To measure total capture cross sections, we used liquid-scintillator detectors which are sensitive to gamma rays but insensitive to the details of the gamma-ray spectrum.

We used this technique to measure the capture cross sections of plutonium-239 over broad ranges of neutron energy. The capture cross section proved to be considerably larger than the value obtained in older measurements, which only yielded the cross section averaged over neutron energy. When plutonium-239 is used for the fuel in breeder reactors, it is important that as many neutrons as possible be available for the breeding process. This larger capture cross section implies that more neutrons are unavailable for breeding. Our result, in conjunction with other measurements, was an important con-

tribution to the facts that led to the decision to stop development of the gas-cooled breeder reactor.

We also measured capture cross sections for gold-197 and holmium-165, which are useful as capture cross-section standards. Measurements on barium-130, tellurium-128, and tellurium-130 provided crucial answers to anomalies in lunar geology studies; measurements on osmium-186 and osmium-187—used as a radioactive clock to measure the age of the solar system—helped make astrophysical dating methods more precise.

In addition to measuring total neutron-capture cross sections, we have measured the details of the spectrum of gamma rays emitted during neutron capture. The excellent energy resolution of a spectrometer consisting of a lithium-drifted germanium detector with a surrounding sodium iodide anticoincidence counter allowed us to determine the intensity of individual transitions between states in the excited nucleus. With such information, we could test various nuclear models that have been proposed to describe the neutron capture process. For example, recently measured gamma-ray spectra from neutron capture on tantalum-181 (at incident neutron energies between 2 and 10^5 eV) suggest a deviation from the statistical processes usually associated with γ -decay in heavy nuclei.

Neutron Total Cross Sections. In yet another approach to neutron measurements, we determined neutron total cross sections. Using the short-beam-burst (5-ns) capability of the LLL linac, we measured high-resolution neutron total cross sections with detectors at the end of the aboveground 250-m flight tube. Such experiments served as a sensitive probe of the validity of the statistical nuclear model. For instance, in a recent experiment on the closed-shell nucleus of yttrium-89, it was found that the behavior of the neutron-nucleus interaction as reflected in the level densities deviated from the standard statistical model.

GAMMA-RAY PRODUCTION

Our linac also contributes to experiments with secondary beams of gamma rays. For example, we produce high-energy bremsstrahlung to make

radioactive isotopes for nuclear medicine. In the mode for maximum beam power, our linac can provide average beam currents of nearly 1 mA in an electron beam with an energy ranging from 30 to 100 MeV, consisting of 300 pulses per second, each with a 3- μ s duration. A platinum production target is generally used to optimize the bremsstrahlung flux.

High-energy bremsstrahlung has been used to produce radioactive isotopes of oxygen and nitrogen, which are useful in life-process studies on dogs. In particular, these radioisotopes have permitted the *in vivo* monitoring of lung damage resulting from ozone inhalation. The decay products of nitrogen-13 were detected by a special multiscintillator positron camera built at LLL. Figure 5 shows the spatial distribution obtained. Preliminary results indicated a significant improvement in the ability to detect ventilation changes in the lung due to ozone inhalation.

POSITRON PRODUCTION

In the production of positrons, the primary electron beam strikes a conversion target usually placed at the output end of the accelerator. This heavy-metal (usually tantalum or tungsten) positron-production target generates bremsstrahlung, and a significant fraction of these photons forms electron-positron pairs in subsequent interactions within the same target. The target thickness is chosen to maximize the yield of positrons. A magnetic beam-transport system filters out all particles except those in a narrow, selected momentum band. In some experiments, the positrons are accelerated first to higher energies before momentum selection is made.

These positrons are used to produce monoenergetic gamma rays for photonuclear (photoneutron and photofission) experiments. In-flight positron annihilation in a second converter target produces gamma rays with a well-defined energy slightly greater than the positron energy. The gamma-ray energy can be tuned to satisfy the demands of the experiment. Monoenergetic gamma-ray intensities obtained with this technique at LLL have been among the highest in the world. We have

Fig. 5. Spatial distribution of nitrogen-13 in a live dog's lung as "seen" by an Anger positron camera. The colors indicate different concentrations of the nitrogen-13 isotope within the lung. Time-dependent, local changes in the ventilation caused by air pollutants, e.g., ozone, can be detected with this technique.

used them in a systematic study of photoneutron reactions in about 65 isotopes.

Our photonuclear program at the 100-MeV linac has recently emphasized the study of the fission process induced by gamma rays (photofission). In collaboration with Los Alamos scientists, we have investigated eight nuclei so far: thorium-232, neptunium-237, plutonium-239, and five isotopes of uranium. Figure 6 shows the fission cross section of uranium-238 decomposed into (γ , f) and (γ , nf) components in the 6- to 18-MeV range. The (γ , f) notation means that gamma rays impinged on a target and that fission resulted (first-chance fission); the (γ , nf) notation means that fission resulted after neutron emission (second-chance fission). By using photons to initiate fission, we can study those processes in nuclei that are difficult or impossible to study with neutron-induced fission. The data from Fig. 6, for example, may be used to infer the neutron-induced fission cross section of uranium-237. This inference is necessary because the half-life of uranium-237, about seven days, is too short for

Fig. 6. Photofission curves showing decomposition of uranium-238 into first- and second-chance fission components. The upper curve represents fission initiated by gamma rays without the intervening emission of neutrons (s, f); the lower curve represents fission after ejection of neutrons (s, n f). The second-chance (s, f) fission cross sections may be used in inferring the neutron-induced fission cross sections of uranium-235, an isotope too short-lived for direct measurements.

us to use it as a neutron target. Furthermore, the data from photofission are, in principle, easier to compare with the predictions of theoretical models.

These examples of measurements with the high-intensity beams of our 100-MeV linac indicate the variety of applications made possible by this versatile machine. By providing data for both basic research and applied problems, this accelerator will continue to be a vital tool for our scientific community.

Key Words: electron linear accelerators; fission cross sections; gamma rays—production; linac; linear accelerators; neutron cross sections; positrons.

NOTES AND REFERENCES

- i. For more information on fission cross sections, see the June 1977 *Energy and Technology Review* (UCRL-52000-77-6), p. ii.

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

Car for Tomorrow: A Quasi-Electric-Drive Vehicle (*June 1977*)

Transportation's Role in the Energy Problem (*March 1977*)

The Methanol Engine: A Transportation Strategy for the Post-Petroleum Era (*December 1976*)

ENVIRONMENT AND SAFETY

Phantom Construction: Building a Torso Manikin for Whole-Body Counting (*December 1976*)

Getting the Facts About Ozone (*November 1976*)

FOSSIL ENERGY

Progress in Oil-Shale Research (*February 1977*)

Hoe Creek No. 1: An *In Situ* Coal Gasification Experiment (*January 1977*)

LABORATORY TRENDS

Continuing Education at LLL (*May 1977*)

The Laboratory: Retrospect and Prospect (*February 1977*)

Achievements and Developments at LLL (*February 1977*)

NATIONAL SECURITY

The Livermore Pool-Type Reactor (*June 1977*)

Imaging Implosion Dynamics: The X-Ray Pinhole/Streak Camera (*December 1976*)

Soviet Experience with Peaceful Uses of Nuclear Explosions (*September 1976*)

NUCLEAR ENERGY

Western States Uranium Resource Survey (*May 1977*)

Safety and Safeguards: Defining the Issues (*October 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

Wind-Energy Assessment (*June 1977*)

Geothermal Energy Development at LLL (*May 1977*)

Energy Conversion Engineering (*May 1977*)

Direct Energy Conversion for Fusion Reactors (*March 1977*)