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The cover

A high-resolution flow cytometer developed in the Biomedical Sciences Division at LLNL provides excellent resolution and flexible use of multiple dye combinations in automated cytometry. Using flow cytometric and sorting techniques, we can excite fluorescent dyes taken up by cells or subcellular particles and sort out those with different properties. The mezzotint on the cover represents a stream of individual cells in liquid suspension passing through the flow chamber. Here, the stream is intersected by a laser beam that stimulates fluorescently labeled cells in the stream to emit light that can be collected and analyzed.

The article on p. 1 describes the use of automated flow cytometry to study hemoglobin mutations in human red blood cells, with the goal of developing accurate techniques to monitor the exposure of individuals to potentially carcinogenic agents in the environment.

About the journal

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

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Brief

Hypervelocity railgun experiments

We have just received a joint contract with LASL from the Army Armaments Research and Development Command (ARRAD-COM) and the Defense Advanced Research Projects Agency (DARPA) to develop an advanced hypervelocity railgun design based on very promising preliminary experiments conducted jointly with LASL. The LLNL portion of the project is funded through the Non-nuclear Ordnance Program.

Hypervelocity projectiles, traveling at more than 5 km/s, have many uses in basic and applied research. They are useful for characterizing reentry-vehicle drag and ablation on entering the atmosphere, for example, and in creating high pressures for equation-of-state studies. Other potential applications include a variety of weapons as well as impact and penetration studies aimed at improving both projectiles and armor.

In our recent experiments we constructed the railgun launchers and LASL built the magnetic-flux-compression generators (MFCG) that powered them. The railgun offers an alternative method of launching massive projectiles. Unlike conventional equipment, the railgun can be optimized to launch a projectile in a shorter distance and with a precise velocity. Furthermore, it may be capable of launching small projectiles at higher velocities than any other known method. To date the team has designed and fabricated prototype MFCGs and launchers

and, at LASL's test facilities, has successfully launched 3-gram polycarbonate cubes at velocities up to about 9.9 km/s.

A railgun is essentially a linear dc motor consisting of a pair of rigid parallel bars that carry current to and from a small interconnecting movable conductor. The connecting link functions as an armature while the parallel rails serve as a single-turn field winding. The Lorentz force resulting from the armature current interacting with the field generated by the rail current accelerates the armature and projectile (Fig. 1). In a square-bore gun

like ours, a 1-MA current will generate a force of about 150 kN and accelerate a 3-gram projectile at 50 000 km/s² (about five million times normal gravity).

We fabricated our railguns of 19-mm-square copper bars, insulated and supported by epoxy loaded with size-graded silica grains and enclosed in a thick-walled aluminum vessel (76 mm i.d.) evacuated to minimize drag on the projectile. The dielectric and the rails fill the space around the bore and prevent the plasma-arc armature from bypassing the projectile. The aluminum tubing supports the inner components against the enormous forces (about 30 MN) exerted by the massive current flowing through the rails for more than 400 μ s.

Our collaborators at LASL made the power source for the railgun (the MFCG, which operates by explosive compression) from a pair of simple U-shaped copper channels fitted around parallel iron bars 5 cm wide and 2.4 m long, spaced 5 cm apart. One channel was lined with sheet explosive. A capacitor bank establishes an initial current in the MFCG inductor. A detonator at the rear of the MFCG then ignites the sheet explosive, which drives one of the two current-carrying copper channels toward the other against the outward magnetic force, decreasing the inductance of the current loop and thereby sustaining the current pulse into the railgun. The iron bars tamp the explosion and retard the expansion of the unimploded regions. For

future experiments it may be possible to design a railgun that can be reused.

Table 1 summarizes the preliminary data obtained from five experiments. In two cases the length of the accelerator was 0.9 m and in three it was 1.8 m. In all five experiments, the projectile was a 12.5-mm cube of Lexan polycarbonate plastic backed on the plasma side by a layer of fibrous shock absorber/ablator 2 mm thick.

In the series of experiments, we used higher and higher currents to increase the acceleration and launch velocity. Preliminary analysis of the data indicates that we achieved launch velocities as high as 9.9 km/s. Most of the projectiles remained intact even though they underwent accelerations of up

Table 1 Preliminary results of railgun hypervelocity experiments.

Experiment	1A	1C	2A	2B	2C
Accelerator length, m	0.9	0.9	1.8	1.8	1.8
Initial current, kA	285	~450	440	~640	640
Peak current, kA	575	~800	~800	~970	965
Peak acceleration, kN/s ²	17 000	~34 000	~34 000	~50 000	50 000
Launch velocity, km/s	2.8	~5.6	~5.4	~9.9	~9.9
Projectile integrity flash x ray	Whole	Half	Whole ^a	.. ^b	.. ^c

^a See Fig. 2.

^b X-ray flash misfired; no x-ray photograph obtained.

^c X-ray flash fired late, missing the projectile. However, a fragment of the projectile was recovered after launch.

to 50 000 km/s² and stresses about 13 times their elastic strength.

In all but the two fastest launches, we obtained flash radiographs of the projectile in transit through the atmosphere (about

2000 m above sea level). Figure 2 is an x-ray shadowgraph of one of the projectiles after 25 cm of travel in the air (50 cm beyond the end of the rails). We are now analyzing the railguns for ways to improve the next generation of launcher.

The focus of our further research, for which we have received DARPA/ARRADCON support, will be on increasing the bore of the launcher and the mass of the projectile, on developing a gun with replaceable components, on testing various design and material options, and on developing improved MFCGs with the higher currents and longer pulse lengths needed to drive more massive projectiles. We are also considering other railgun applications that may deserve development.

In summary, we found that:

- Railguns can be effectively powered by magnetic flux compression generators.
- Currents of over 600 kA can be maintained and used in a railgun.
- Projectiles can survive the railgun launch process despite stresses that greatly exceed their elastic limit.
- Velocities of almost 10 km/s were inferred from the data, and far higher velocities are theoretically possible with further development.

For further information contact Ronald S. Hawke (422-8679).

Fig. 2 A computer-enhanced image from an x-ray shadowgraph of the Lexan projectile travelling at about 5.5 km/s, 50 cm beyond the end of the rails and 25 cm into the air. The projectile was originally a cube; atmospheric ablation has mushroomed the forward surface.

Detecting genetic damage in humans: somatic-cell mutation as a predictor of cancer risk

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We have developed a promising technique for detecting the immediate effects of cancer-causing agents in the environment directly in the cells of exposed individuals. This method is based on the fact that chemicals and physical agents (such as radiation) known to cause cancer produce genetic damage in the form of cell mutations. Recently, this fact has been exploited to develop screening assays that identify cancer-causing chemicals (carcinogens) by their ability to induce mutations in simple organisms such as bacterial, yeast, or mammalian cells grown in culture.

Our technique, however, can detect mutations in vitro, using the genetic material of normal human cells within the body. We look for mutations that change the protein molecules called hemoglobin that are contained in red blood cells. To identify the rare red cells that contain mutation-altered hemoglobin, we use fluorescently tagged antibodies that bind tightly only to altered molecules. Flow cytometry allows us to separate cells containing variant hemoglobins labeled with fluorescent antibodies from cells with normal hemoglobin. The frequency of such variant cells in the blood of a normal individual may be taken as a measure of that person's accumulated genetic injury and thus may serve to monitor exposure to potentially carcinogenic agents in the environment.

In recent years, there has been a growing awareness that environmental conditions can have important effects on human health, the most significant example being the potential for industrially produced pollutants to cause cancer. Cancer symptoms may appear long after exposure to complex mixtures of environmental agents, the effects of which are influenced by many individual differences of genetic makeup, dietary habits, and lifestyle. All of these factors then contribute to the statistical probability that a given individual will develop cancer. To control human exposure to carcinogens and to improve cancer prevention, we must be able to detect the effects of cancer-causing agents on

individuals long before disease symptoms appear.

The classical approach has been to identify cancer-causing agents by exposing small animals to high levels of suspect chemicals and waiting for them to develop tumors. Such studies have implicated chemical agents in causing cancer, but the approach is slow, relatively insensitive, and expensive. Most important, the results are very difficult to extrapolate to humans chronically exposed to low levels of complex mixtures. We need a way to detect and quantify the immediate cancer-causing effects of

chemical agents directly in human beings.

Recently, cancer-causing chemicals have been found to produce their initial effects by inducing genetic damage in the form of mutations. This discovery has made possible the use of rapid and economical *in vitro* screening assays for these chemicals, using bacterial and mammalian cells in culture. These assays test chemical compounds and complex mixtures for their capacity to induce mutations and, by inference, for their potential to cause cancer in animals and humans. While such tests have proved to be useful for identifying chemicals that are toxic to genes, it is uncertain to what extent the results can be applied to provide quantitative risk assessment for people.

Detecting mutations in human cells

Experience with *in vitro* cellular assays suggests that a sensitive assay might be developed to detect mutations directly in human cells. We could then monitor and control exposure to agents causing these mutations and could also explore the relationship between the presence of such mutations and the development of cancer.

Mutations are expressed in two ways, depending upon whether

reproductive (gametic) cells or non-reproductive (somatic) cells are involved. If reproductive cells suffer mutagenic damage, the resultant sperm or ova may carry mutations that can be transmitted to the next generation in the form of birth defects in the offspring of the affected individual. Determining the frequency of such events has been the classical focus of most studies of mutation in humans. However, these studies can be done only by observing large numbers of people over long periods of time. They are slow, insensitive, and entirely retrospective.

In contrast, both gametic and somatic cells may be examined directly for the existence of mutations. By examining large numbers of cells from one exposed person, we could characterize the amounts and kinds of genetic damage that individual has incurred. We could examine small numbers of exposed persons repeatedly throughout their lives, quantitating accumulated genetic damage and evaluating the effects of cumulative damage from chronic exposure to the complex chemical environment.

To understand how we are able to detect mutations in single cells, we must consider the molecular mechanisms of mutation and the subsequent molecular biology responsible for expressing mutations in cells. As detailed in the box on p. 4, mutations are changes in the instructions governing the life

of the cell. A complete set of "blueprints" for synthesis of the protein molecules that make up the structure and metabolic machinery of the cell is encoded in the DNA molecules of each cell's chromosomes. These blueprints are the genes.

Chemicals capable of causing mutations in human cells do so by modifying the DNA. Every human cell contains in the DNA of its 23 pairs of chromosomes genes for at least 100,000 different proteins, and chemical damage to the DNA may result in an alteration in any one of these genes. As a result, the protein corresponding to the altered gene will be constructed incorrectly. By mechanisms we do not yet fully understand, such damage can occasionally cause a normal cell to become malignant. Thus, associated with each mutational event is a statistical probability of the ultimate development of cancer.

Ideally, we would like to detect in cells the first step in this process, that is, damage to the DNA itself. However, such a small fraction of the total DNA is modified that at present this approach is not technically possible. Instead, we look at the next step, for incorrectly constructed protein molecules that are expressed as a result of the initial DNA damage. These variant protein molecules can be detected because many copies (in some cases as many as 300 million per cell) of a protein molecule are made from a single DNA message.

To conveniently apply an assay based on single somatic cells, the sampled tissue should consist of a permanent population of cells in which mutations can occur and be

subsequently expressed in the affected cells or in their daughter cells. Also, the tissue should be easily accessible and capable of providing a homogeneous population of single cells for analysis. Finally, a method must exist for positive detection of the altered protein molecules.

The tissue that forms human red blood cells meets these criteria. Mature circulating red blood cells (erythrocytes) are produced in

tremendous numbers through a complex path of differentiation and cell maturation for a permanent pool of stem cells located in the bone marrow. From stem cell to erythrocyte, between 8 and 14 cell divisions occur, so each progenitor cell can produce between 256 and 16 384 daughter cells. A mutation that occurs in any of the red cell precursors should appear in the mature erythrocytes, if the genetic damage does not kill the cell.

Variant hemoglobins as evidence of genetic damage

We have chosen to study mutations occurring in the gene for the protein hemoglobin, the most abundant and best characterized protein in human red blood cells. This vital protein is responsible for transporting oxygen from the lungs to the peripheral tissues. Many variant hemoglobins have been isolated from individuals who carry a mutated hemoglobin gene as a result of a germinal mutation—one occurring in a reproductive cell—in one of their ancestors. Biochemical analyses of these altered hemoglobins have shown that the vast majority occur as a result of a single base change in the DNA message, as illustrated in the box on p. 4. The result is that the amino acid that normally appears at a specific position in the sequence making up the hemoglobin molecule is replaced by another amino acid. Figure 1 shows the normal amino acid sequence of hemoglobin and all the known amino-acid substitutions that have been found expressed, one at a time, in rare individuals.

The existence of these variant hemoglobins in rare individuals as a result of germinal mutations suggests that, in genetically normal individuals, mutations of the same type may occur as the result of genetic damage to the DNA of their

The molecular basis of mutation

Physical and chemical agents that can cause cellular mutations act by damaging the DNA molecules of the cell. The DNA carries the genetic instructions for the synthesis of proteins, very large, complicated molecules that function in living cells to catalyze thousands of biochemical reactions, transport small molecules from place to place, form self-assembling cellular structures, control the synthesis of other proteins, etc. For each of these tasks the cell makes a different and specific protein, the coded description of which is contained in a segment of DNA called a gene.

Proteins are linear polymers of small organic molecules called amino acids. Twenty structurally different amino acids are combined in varying numbers to form a unique sequence for each protein, and it is the description of this amino-acid sequence that is contained at the specific gene location in the DNA for each protein. Mutations in the DNA, therefore, ultimately result in the incorrect construction of proteins. Since proteins constitute the cellular metabolic and structural machinery, the presence of altered proteins can have important, and sometimes lethal, effects on the life of the cell.

We can use the protein molecule hemoglobin and its gene to demonstrate how the information needed to construct proteins is stored in the DNA and decoded in protein synthesis, and how it can be modified by mutation.

Like all DNA, the hemoglobin gene is a double threadlike structure (see figure below) composed of

a sequence of four different nucleotides (denoted here by A, C, G, and T) encoded into a long, continuous message. This four-letter code contains the information required for the synthesis of hemoglobin. This process begins when the nucleotide sequence constituting the hemoglobin gene is copied as messenger RNA. The messenger RNA, with the same nucleotide sequence as the DNA except for replacement of T by a very similar nucleotide labeled U, then serves as a template for the construction of hemoglobin molecules.

The nucleotide sequence of the messenger RNA is read and decoded, three nucleotides at a time, by transfer-RNA molecules (see first figure, facing page), each of which contains a complementary triplet of nucleotides (A binding with U, and C binding with G). Each transfer RNA carries a specific amino acid corresponding to a given triplet; for example, a transfer RNA with the recognizing triplet -G-C-C- always carries the amino acid arginine (Arg or R). Since the four nucleotides can be combined three at a time to form 64 (4^3) different triplet sequences, this coding system contains (redundantly) all the information to specify the correct selection

of any of the 20 different amino acids used in protein synthesis. As each amino acid arrives at the template, it is chemically bonded to the growing protein chain, then decoupled from its transfer-RNA carrier. Shown below are the actual nucleotide and amino acid sequences for the amino acid positions 5 through 7 in human hemoglobin. This translation

process continues until the chain is terminated by a "stop" triplet of nucleotides signaling completion of the hemoglobin molecule consisting of 146 amino acids. Each molecule takes about 3 minutes to complete.

Mutations are changes in the genetic instructions to the cell (see next figure). The molecular basis for mutation thus is an alteration in the nucleotide sequence coding for a given protein. Chemicals produce mutations by reacting with the DNA molecule, but such chemical damage occurs very infrequently, and cells have enzyme systems that usually recognize and repair damaged portions of the DNA, so the intact nucleotide sequence is retained and the correct message restored.

However, occasionally the damage is not recognized or is incorrectly repaired, and an altered nucleotide sequence may result. Shown above is the mutation associated with sickle hemoglobin. At the sixth triplet, A is replaced by U, so that during the translation process valine (Val) is substituted for glutamic acid (Glu) at the sixth position of the hemoglobin molecule. This type of alteration (the substitution of an incorrect amino acid at any point in the sequence) is relatively small; other mutational events can produce more extensive alterations such as the deletion or insertion of one or several amino acids or the loss of an entire protein. All of these changes can have profound effects on the biology of the cell.

somatic blood-forming stem cells, giving rise to daughter erythrocytes that contain a variant hemoglobin. The frequency with which cells containing these variant proteins occur in the blood of an individual presumably reflects the accumulated genetic injury sustained by that person's stem cells.

To study the frequency of variant hemoglobins in circulating red blood cells, we must be able to differentiate variants from the normal form. Our technique is based on the immune response in animals. We use a class of protein molecules called antibodies, which are produced in an organism in response to an immunologic challenge by a molecule—called an antigen—that is foreign to that organism. Once formed, an antibody molecule encountering its antigen recognizes it and binds tightly to it.

It is possible to produce antibodies for specific variant hemoglobins.¹ We prepare antibodies that are specific for hemoglobin S, which has a substitution of the amino acid valine (Val or V) for the amino acid glutamic acid (Glu or E) at the sixth position on the hemoglobin chain. Then we attach a fluorescent molecule to each of these antibody molecules. When cells that contain

the variant hemoglobin S are exposed to this antibody, they will bind the antibody and thus will be fluorescently labeled.

Identifying variant hemoglobins with flow cytometry

Few red cells in the blood of a normal person will contain hemoglobin S, so we must examine very large numbers of cells in order to detect any variants. We have devised an automated method for doing this. The red cells are chemically treated to covalently link a portion of the intracellular hemoglobin to the cell wall. The cells are then treated to produce holes in the cell membrane, allowing the cell contents (predominantly unbound hemoglobin molecules) to escape. The empty red blood cells, called ghosts, are first washed and then incubated with fluorescently labeled antibody, which enters the ghost cells through the holes that remain in the cell membrane.

Figure 2 is a fluorescence photomicrograph of antibody-labeled red blood cell ghosts. In this preparation all of the ghosts contain hemoglobin recognized by the antibody, so all are fluorescently labeled. In a preparation of blood from an individual who carries genetically normal hemoglobin genes, the only labeled cells will be those very rare cells that contain

hemoglobin S derived from a particular somatic mutation of a stem cell.

Flow cytometry (Fig. 3), developed in large part in the Biomedical Sciences Division at LLNL,² is used to sort the labeled cells. Large molecules (in our experiments, antibodies) in intact cells are stained with fluorescent dyes, and the stained cells are suspended in an aqueous buffer solution. The cells flow single file across a beam of intense laser light that excites the dye to fluoresce. The fluorescent flash from each cell is detected by an optical system and converted to an electrical pulse that is integrated, amplified, digitized, and stored in the memory of a multichannel analyzer. The flow machine can

Fig. 2 Human red blood cell ghosts labeled with fluorescent hemoglobin S antibody. These ghost cells contain hemoglobin crosslinked to the membrane of the cell. Binding of the fluorescent antibody to the hemoglobin produces the green membrane-specific fluorescence.

also sort fluorescent objects from the sample by electrostatically deflecting the small droplets that contain them. Such sorted material may then be examined microscopically.

Data are received from the flow cytometer as three-dimensional population histograms that characterize (1) the measured values of fluorescence intensity proportional to the amount of bound antibody and (2) the amount of laser light scattered from the cell (a rough measure of size) for all the ghost cells in the sample. By scanning dense suspensions of red blood cell ghosts at rates exceeding a million

ghosts per second, we can detect those fluorescent objects suspected to be antibody-labeled ghost cells.

A display from the flow cytometer is shown in Fig. 4 for a sample of ghost cells from a person carrying the hemoglobin S germinal mutation. The peak generated in the histogram thus defines the range of fluorescent intensity in which we would expect to find, in a sample from a normal individual, any rare mutant ghost cells that have formed as a result of a somatic mutation. We have analyzed samples from normal individuals, sorting onto microscope slides objects that produce signals

in this area. Fluorescent debris dominates the sorted objects, but we do observe ghost cells labeled with antihemoglobin S in normal samples at a frequency of one ghost cell to 10^7 to 10^8 normal cells. Similar results have been obtained using another monospecific antibody, the one that binds hemoglobin C, in which the amino acid lysine substitutes for the amino

Fig. 4 Three-dimensional histogram of red blood cell ghosts that contain hemoglobin S. The cells were chemically treated to covalently link a portion of the intracellular hemoglobin to the cell wall and then were treated to produce holes in the cell membrane, allowing the cell contents (mainly unbound hemoglobin) to escape. The empty cells are called ghosts. These were washed and incubated with a fluorescently labeled antibody, which enters the cells through the holes in the cell membrane. The antibody binds to those cells that contain hemoglobin S linked to the cell wall. This histogram displays the range of fluorescent intensity we expect for the rare antihemoglobin-S-labeled cells detected in the blood of a genetically normal individual.

acid glutamic acid, also at the sixth position on the hemoglobin chain. Thus, these two mutations appear to occur at about the same background frequency in normal unexposed individuals.

Future work

Future work calls for validation of our approach by (1) demonstrating that labeled cells appear as a result of mutation, (2) applying the assay to appropriate groups of human subjects, and (3) expanding the approach to additional gene products in red blood cells and other cell types. First, genetic and biochemical tests will be applied to confirm that the rare labeled ghost cells contain a variant hemoglobin. Next, control populations of normal persons will be studied to determine the repeatability of the assay when applied to any one individual and the variability among individuals, and to determine if

there is an age effect (we might expect stem-cell mutations to accumulate throughout an individual's lifetime, so old people would have a higher frequency of variant cells than young people). Then, the assays can be applied to individuals known to have been exposed to high concentrations of mutagens, for example, cancer patients undergoing chemotherapy with genotoxic drugs.

If a dose response can be observed in such patients, that is, if a direct relationship is found between exposure and the number of cells that contain variant hemoglobin, individuals suffering more subtle chronic occupational exposures to mutagens can be examined. Finally, we must evaluate and apply the technique to other red cell proteins or proteins expressed in other cell types. With such a battery of markers we could compare the frequencies of different classes of mutations in differing physiology. Work is currently under way on some of these approaches.

This experimental approach ultimately should allow accurate monitoring of individual environmental exposure to potentially carcinogenic agents. With somatic-cell-based mutation assays, it may be possible to analyze an individual's accumulated risk by using stem cells as *in vivo* biological dosimeters. Long-term studies could then address fundamental questions in human biology: Do body cells integrate mutations throughout life, as the mutational theory of aging and cancer predicts? Are such assays sensitive enough to monitor environmental exposure and thereby identify atypically vulnerable individuals? Finally, and most important, does an increased frequency of somatic-cell mutations indicate an increased probability that an individual will develop cancer in later life? Answers to these questions are presently a long way off, but experimental approaches like those described here offer great promise of ultimate success.

Key words: antibodies; antigens; blood; cancer; flow cytometry; hemoglobins; immunology; mutagens; mutations; proteins.

Notes and references

1. Our collaborator, Dr. George Stamatoyannopoulos, at the School of Medicine of the University of Washington, has successfully produced several antibodies specific for single amino-acid-substituted hemoglobins.
2. The development of high-resolution dual-laser flow cytometry was described in the *Energy and Technology Review* for December 1978 (UCRL-52000-78-12), p. 27.

Argon x-ray line imaging: a compression diagnostic for inertial confinement fusion targets

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We have been using various techniques to measure the ion temperature and density of the deuterium-tritium (D-T) fuel in an inertial confinement fusion (ICF) target in order to determine our progress toward the goals of significant thermonuclear burn and net energy gain. The ion temperature of the fuel can be inferred from the measured yield of the fusion-reaction (14-MeV) neutrons; measuring the final fuel density is more difficult.

New techniques—including argon x-ray line imaging and neutron activation—let us infer the compression obtained with our intermediate-density targets. Argon x-ray line imaging measures the compressed fuel volume directly by forming one-dimensional images of x rays from argon gas seeded into the D-T fuel; the photon energies of the x rays are recorded on the film of a diffraction-crystal spectrograph. Neutron activation, which detects activated nuclei produced by the interaction of 14-MeV neutrons with selected materials of the target, allows us (with the help of a hydrodynamics simulation code and knowledge of the total number of activated nuclei and the neutron yield) to calculate the final compressed fuel density. Argon x-ray line imaging appears to be a valid fuel-compression diagnostic for final fuel densities in the range of 10 to 50 times liquid D-T density (2 to 10 g/cm³).

The objectives of the Laboratory's inertial confinement fusion (ICF) program are twofold: (1) to develop the capability to study nuclear weapon physics for the weapons program, and (2) to develop ICF technology for civilian energy production. We have been conducting our experiments on thermonuclear fusion microexplosions with focused high-power lasers. In a typical experiment, the light from a powerful pulsed laser such as Shiva¹ is focused on a hollow glass pellet (target) about 140 μ m in diameter coated with various thicknesses of plastic and containing a high-pressure mixture of deuterium-tritium (D-T) fuel. As

the incident radiation from the laser heats and compresses the target, the target is driven to thermonuclear burn conditions.

Two parameters indicate how successful we are in achieving thermonuclear burn: the ion temperature and density of the D-T fuel during the burn. The ion temperature of the D-T fuel at burn time can be inferred from the measured yield of fusion-reaction (14-MeV) neutrons. Measuring the

ion density of the fuel at burn time is more difficult.

We usually determine final fuel density by measuring the size and shape of the compressed fuel volume. Images of this volume are formed either by x rays radiated into an x-ray microscope by the compressed shell or by alpha particles produced in the fusion reaction and detected by a Fresnel zone-plate camera (a camera using coded-imaging principles).² Both imaging techniques work well for an exploding-pusher target whose thin glass shell decompresses explosively during implosion.

To achieve higher fuel compression, however, the fuel and nearby regions of the glass pusher must be protected from preheat by energetic electrons and x rays. Our new targets address the electron preheat problem by the addition of a relatively thick layer of plastic (15–50 μm CH). These coating thicknesses are somewhat larger than mean electron ranges, thus advancing our work toward ablatively driven targets³ (in which the target thickness is much greater than the deposition length). Although these new “intermediate-density” targets attain higher fuel compressions, they make diagnostics more difficult because the final glass pusher state is also more dense and opaque, and, with the power limitations of present-day drivers like Shiva, relatively

cold (about 1 keV or about 1.1×10^7 K) at burn time.

As a consequence, the transmission of x rays emanating from the fuel–pusher interface is greatly reduced, denying us a previously valuable source of compression information (see box on pp. 14–15). To counteract this loss of information, even more penetrating x rays must be used for diagnostics. We must use higher Z seed gases with higher energy resonance levels and develop new x-ray imaging capabilities. Furthermore, the reaction product alpha particles no longer escape the target, and we are again denied a valuable tool, which must be replaced by the use of longer range particles. As we proceed to ever higher fuel densities, we must develop a new series of measurement techniques.

We have been using several new techniques to measure the compression obtained with intermediate-density targets: neutron activation of target materials at the time of peak burn, argon x-ray line imaging, and high-energy x-ray zone-plate images. The neutron-activation technique for intermediate-density (about 2 g/cm^3) target experiments performed on the Shiva laser involves the detection of activated nuclei produced by the interaction of the 14-MeV fusion neutrons with atoms in the glass shell. By knowing the total number of activated nuclei and the neutron yield, we can calculate the glass attenuation length from which, with the help of a hydrodynamics simulation code, we can

derive the fuel density. The argon x-ray line technique, on the other hand, measures the size of the compressed fuel volume directly by forming one-dimensional images of x rays radiated not by the shell but by a small amount of argon gas seeded into the D–T fuel.

To isolate the narrow x-ray lines of argon from the continuous spectrum radiated by the glass, we need a high-resolution diffraction-crystal spectrograph. Figure 1 shows a miniature crystal spectrograph designed to be used close to the target for maximum sensitivity (3.5 cm from the center of the crystal). A 6.3-mm-thick tantalum block located above and ahead of the flat diffraction crystal shields the spectrograph’s 65-mm-wide film from direct exposure to target radiation. As x rays diverge from the target, they strike the crystal over a limited range of incidence angles. For each angle, the crystal selects, by the Bragg diffraction process, a unique x-ray photon energy for reflection to the film. (See box on p. 16.)

The x-ray beam that reaches the crystal is collimated by a fine slit 20 to 30 μm wide placed between the target and the crystal. The axis of the slit is aligned parallel to the crystal’s plane of dispersion, causing the spatial distribution of the source to be recorded from side to side on the 65-mm-wide film. The close spacing between the slit and the target (5 mm) produces an image magnification of 12. In a sense, we are using a “one-dimensional” pinhole camera.

With appropriately thin slits, this argon x-ray line-imaging technique appears to produce valid fuel-compression measurements for

final fuel densities in the range of 10 to 50 times liquid D-T density (2 to 10 g/cm^3). Targets expected to achieve higher compressions will use shells that are too thick to transmit the argon x-ray lines. The neutron-activation technique, on the other hand, will be applied to targets that can achieve much higher final fuel densities. The longer range value of argon imaging and other techniques is to corroborate the neutron-activation

technique for medium-density targets (targets that achieve compressions in the range of 10 to 50 times liquid D-T density). Preliminary corroboration of these techniques has been obtained in a recent series of target shots at the Shiva laser facility. A refinement of that work with higher seed levels and narrower slits is planned.

Measurements using targets seeded with argon or neon have also been made at several other

inertial confinement fusion laboratories, notably the Rutherford Laboratory, the University of Rochester Laboratory for Laser Energetics, and the Los Alamos National Scientific Laboratory.⁴ Observations of the spectral distribution of the seed-gas x-ray lines, as well as imaging, have provided information on the condition of the fuel at burn time. For example, the electron temperature can be derived from the intensity ratios of lines radiated by the highly ionized seed gas. Under certain circumstances, the spectral width of the lines can give an independent measurement of the fuel-plasma density from the phenomenon known as Stark broadening.

Argus test series

We tested the argon x-ray line imaging technique with exploding-pusher targets at the Argus laser facility to determine if the x-ray lines radiated by hydrogen- and helium-like argon (argon whose ions have only one or two electrons left) were strong enough to be visible above the continuum radiation. Also, we wanted to compare the argon line images with those produced by the zone-plate camera.

Fig. 1 Miniature x-ray crystal spectrograph designed to image the argon and silicon x-ray lines radiated by the inertial fusion targets used in Argus and Shiva laser experiments. A fine slit on the front of the spectrograph and 5 mm from the target collimates the x-ray beam that reaches the diffraction crystal, thereby constraining x rays from any given region of the target to fall on a given area of the spectrograph's 65-mm-wide film. The center of the diffraction crystal is 3.5 cm from the target. By changing the angle the crystal makes with the spectrograph's line of sight, we can adjust the range of photon energies the spectrograph analyzes.

We felt it important to verify that the electron temperature in the compressed fuel was high enough to strip most of the electrons from the argon, since only the helium- and hydrogen-like lines of a higher Z element like argon, at energies above 3 keV, could penetrate the glass shell. To ensure that the implosion dynamics of the fuel and its neutron yield would be only slightly altered by the presence of the high- Z gas, we seeded a very small amount of argon gas (about 0.15 mg/cm^3) into the D-T fuel of all our targets. We hoped to show that the targets would perform as typical exploding-pusher targets while radiating argon x-ray lines of sufficient intensity to allow the compression measurement.

One important question about the argon imaging technique that could not be answered directly in the Argus series was whether the times of argon x-ray line emission and of D-T fuel burn coincided. The boundary of the fuel volume converges very quickly during an implosion and, unless the timing is good, the x-ray images will be larger than the fully compressed fuel core. Computer simulations of the implosion (which showed that the high electron temperatures required would be achieved only late in the implosion) suggested that no significant errors would be introduced by this factor, a conclusion we hoped to substantiate by

correlating the x-ray and alpha-particle images.

Test equipment. The glass pellets used in the Argus test series were formed by the liquid-droplet method.⁵ This process starts when acoustic vibration breaks up a jet of glass-forming compounds in aqueous solution into a stream of uniform droplets that pass through a long vertical furnace where they inflate and fuse into hollow glass microspheres. The drop tower for the Argus series was suffused with argon, and the density of argon in the pellets was of the order of 0.15 mg/cm^3 ; the density of the D-T fuel subsequently loaded into the pellets was 5 mg/cm^3 .

An argon-imaging spectrograph (see Fig. 1) and a zone-plate

camera were positioned opposite each other in the Argus target chamber, as shown in Fig. 2. A second imaging spectrograph, modified to image the silicon in the glass pellet shell, was located in a third quadrant of the chamber. This spectrograph was used to determine the extent to which the glass mixed with the fuel during implosion. The plane containing both spectrographs and the zone-plate camera was normal to the direction of propagation of the two opposed laser beams.

The tests. The pellets used in the Argus test series had an initial diameter of $140 \mu\text{m}$ and a wall thickness of $2 \mu\text{m}$. We expected that pellets exposed to the Argus laser beams, each delivering an

Fig. 2 Two x-ray imaging spectrographs (bottom of photograph) and a zone-plate camera (upper left) view the microscopic inertial fusion target (on the tip of the vertical needle-like structure) in the Argus target chamber. The spectrograph at right views x-ray lines produced by argon gas seeded in the target's D-T fuel; the one at left views lines produced by silicon in the glass target shell. The zone-plate camera produces images of the fuel burn region by recording alpha particles created by the D-T reaction.

energy of 300 J in 140 ps, would be compressed to a final diameter of the order of 30 μm and heated to a temperature of 1.5 keV (about 1.6×10^7 K).

Potassium was a significant constituent of the pellet glass (11% by weight), and x-ray lines of this element (with photon energies near 3.5 keV) were observed in the spectra of the argon-imaging spectrograph. The band of photon energies selected by the diffraction crystal for reflection to the spectrograph's 65-mm-wide film ranged from 2.6 to 3.7 keV. This band included the most intense helium- and hydrogen-like argon lines (denoted Ar-He α and Ar-H α), whose energies are 3.14 and 3.32 keV, respectively. We analyzed this band along the length of the film for the instrument geometry shown in Fig. 1.

For a typical test series shot, x-ray images of silicon, argon, and potassium were recorded by the two spectrographs, as shown in the spectrograms of Fig. 3. The lines of silicon and potassium—the glass constituents—were radiated at both the initial target boundary (the region heated by the laser beams) and the fuel core, while the source region for the argon lines was confined to the compressed core. The ratio of intensities of the Ar-He and Ar-H alpha lines indicates a core electron temperature of the order of 1.6×10^7 K. Stark broadening of the lines was not observed.

Test results. We analyzed the argon line images with a computer to correct for the width of the slit and other effects of the argon line-imaging technique. The spatial profiles produced by the analysis are shown in Fig. 4a. The width of the Ar-H alpha image is about 35 μm , and that of the Ar-He

alpha image is somewhat larger. Because the electron temperature in the fuel core increases during implosion, radiation from the lower ionization-state helium-like ions necessarily precedes and thus occurs within a larger volume than that of the hydrogen-like species. An alpha-particle emission profile, scanned in the same direction as the argon images, is shown in Fig. 4b. The width of the emission profile, which is an accurate measure of the burn-region diameter for exploding-pusher targets, is about 30 μm .⁶ Thus there is reasonably good agreement

between measurements of the size of the compressed fuel region obtained by Ar-H alpha imaging and by alpha-particle imaging. The targets performed as typical exploding pushers (in terms of compression and neutron yield achieved) and suggest that the argon seed had no effect on the implosions.

Shiva test series

Test diagnostics. We used the Shiva laser system to drive a series of targets designed to reach final fuel densities of about 10 times liquid D-T density (2 g/cm³). Both

Fig. 3 Spectrograms recorded during an Argus exploding-pusher target shot show that (a) potassium and (b) silicon, the glass constituents, radiated x rays both at the initial outer boundary of the target and from the outside of its compressed core. Argon x-ray lines, however, were radiated only from the inside of the core.

the argon-imaging and neutron-activation techniques proved successful density diagnostics for these experiments.³ In addition, we tested a new application of the

zone-plate-coded technique² to image the target-produced high-energy x rays (5 to 20 keV). All three diagnostics implied final fuel densities of about 2 g/cm^3 .

To measure the density of the compressed D-T fuel at the time of thermonuclear burn, we must either image the burn region to determine its shape and size or measure quantities that can be used directly or indirectly to infer the density of the fuel. The dimensions of the burn region can be found by imaging the thermonuclear burn products (alpha particles or neutrons), by imaging the x-ray emission from seed materials added to the fuel, or by imaging the x-ray emission from the pusher immediately next to the fuel. More explicit information about the density (ρ) or areal density (ρr) of the fuel can be derived from observations of Stark broadening of x-ray spectral lines from seeded fuel or by neutron activation of various materials added either to the fuel or to the target pusher.

Imaging the alpha particles or x rays and analyzing the x-ray spectral lines become increasingly difficult as the fuel and target areal densities increase and thus absorb (stop) more of the emission. This phenomenon can be seen from the accompanying figures.

The top figure shows the fraction of x rays that pass through the glass pusher containing the D-T fuel at peak burn as a function of glass ρr for x-ray energies of 2, 4, and 8 keV. In each x-ray

Applying fusion-density diagnostics

band shown, electron temperature varies from 100 eV (essentially cold values) to 500 eV. Vertical bands are shown for some typical target designs that achieve the final glass areal

densities indicated. These designs are for exploding-pusher targets (EP) and for relatively thick-walled glass shells with varying thicknesses of plastic coating that are expected to achieve final fuel

densities from 10 to 100 times liquid D-T density (2 to 20 g/cm³). Although passage of 2-keV x rays appears high for heated glass (~500 eV), experiments making use of this fact are compromised by localized temperature variations, which affect transmission and also alter the thermal emissions (background radiation). For this reason, higher energy photons, such as 4- to 8-keV x rays, are preferred.

The bottom figure shows the region of applicability for alpha-particle imaging and argon line-imaging crystal spectrograph as a function of target neutron yield and fuel or pusher areal density. A typical intermediate-density target imploded with the Shiva laser has a fuel ρr of about 3×10^{-3} and a neutron yield of 10^8 , making diagnostics by argon imaging and neutron activation of several fuel and pusher additives possible. As the fuel density increases, however, we observe that unless the neutron yield, and hence the fuel temperature, increases significantly, diagnosis of x-ray emission becomes very difficult. Fuel-density determination by neutron activation, however, remains a powerful technique.

Bragg scattering of crystals

High-resolution spectroscopy at x-ray wavelengths less than 1 nm requires the use of natural diffraction crystals, which are analogous to the diffraction gratings used at optical wavelengths. When a polychromatic x-ray beam strikes a diffraction crystal, only a very narrow band of wavelengths is reflected to a detector. The position of the band in the spectrum can be controlled by the choice of crystal and by the beam-crystal geometry.

The atoms in a natural crystal are located in parallel and symmetric planes. The distance between adjacent planes is a constant dimension called the d -spacing (see bottom left figure). As an x-ray beam passes through the crystal at a given angle with respect to the planes, a small portion of the x rays is coherently scattered by the atoms in each plane. The scattered radiation will constructively interfere and produce a strong signal outside the crystal only if the angle of reflection is equal to the angle of incidence and only for x rays whose wavelength is equal to the difference in the beam path length between adjacent planes. The latter condition produces the wavelength selection formula $\lambda = 2d \cdot \sin \theta$, where θ is the angle of incidence shown in the figure. Hence, for a given

crystal (that is, for a given d -spacing), there is a one-to-one correlation between the angle of incidence and the reflected wavelength.

For a steady x-ray source such as an x-ray tube, a spectral analysis over a broad range of wavelengths is obtained by slowly scanning a crystal and detector over the appropriate range in θ . For a short-lived source such as a laser-produced plasma, however, the geometry of the crystal must allow incidence at all angles in the range simultaneously (see bottom right figure), requiring the use of a slit instead of a pinhole on our spectrograph. Furthermore, the detector (photographic film, for example) must be placed so that there is a one-to-one correlation between the angle of incidence and the location at which the reflected ray strikes the detector.

Of the several types of x-ray spectrometers used in the laser fusion program, the crystal spectrograph is particularly useful in determining the temperature and distribution of individual target elements, such as the silicon in the glass pellets. Each element radiates narrow x-ray wavelengths. Only the high-resolution crystal spectrograph, however, can isolate the lines from the continuous spectrum radiated by the laser fusion targets.

The tests. Shiva typically delivered 4 kJ of energy in 200 ps onto the targets, glass shells 140 μm in diameter and 5 μm thick, coated with 15 μm of Teflon. The spectrogram in Fig. 5 shows images due to argon and chlorine. Chlorine, which radiates a helium-like line at 2.79 keV, is apparently a minor contaminant of the plastic coating. Its image forms a smoke ring around the initial outer boundary of the target. In this shot, the core electron temperature apparently was not high enough to strip the argon down to a hydrogen-like species, the Ar-He alpha line, but not the Ar-H alpha line, is shown radiating from the core.

Test results. Figure 6 shows the results of the zone-plate camera measurements. X rays above 5 keV are required in order to penetrate the target's high-density glass pusher. On the other hand, if the x-ray energy is too high, as shown for the 16.5-keV image, not enough continuum x rays are emitted to expose the film. Figure 7 demonstrates the ability of this technique to clarify different portions of the target emission, particularly the compressed core. This information is complementary to that of the line emission and neutron-activation data. In fact, the agreement among the argon-imaging, neutron-activation, and x-ray imaging results is quite good. The agreement in this series of tests suggests to us that neutron activation could be applied to even higher final fuel densities. The major source of error in the argon-imaging data was apparently the

Fig. 5 Spectrogram recorded during a test of an ablatively driven target on Shiva shows that x-ray lines due to chlorine (a contaminant of the target's plastic coating) were radiated at the outer boundary of the target. Since the core electron temperature was apparently not high enough to strip the argon down to a hydrogen-like species, the Ar-He alpha line, but not the Ar-H alpha line, is shown radiating from the core.

(a) Thermal x-ray image (6.5 keV)

(b) Suprathermal x-ray image (16.5 keV)

Dimensions of compressed fuel = 21 X 25 μm

Thermal image-intensity profile

Shot No. 89072310
Laser pulse: 200 ps
Laser energy: 4.1 kJ
Neutron yield: 7×10^8

Fig. 6 Two zone-plate-coded images of the x-ray emission from medium-density (10 to 50 times liquid D-T density) inertial fusion target experiments on Shiva. The outer ring in both images corresponds to the initial position of the glass shell. (a) The 6.5-keV image (thermal region) shows the compressed fuel-pusher interface (center). (b) The 16.5-keV image (suprathermal region) does not show this interface because there is no longer a sufficient flux of x rays to form an image of the core. The x-ray emission from the core for lower energies (not shown) does not reveal any distinguishing features, demonstrating the value of multispectral image discrimination.

need to assume symmetry in the shape of the fuel core, although slit size and signal-to-noise ratio considerations are also of concern.

Conclusions

We have demonstrated the ability of argon x-ray line imaging to measure a dimension of the burn region of a high-compression inertial fusion target. There are,

however, two obvious improvements that could be made in the technique. First, a spectrograph capable of forming two-dimensional images while retaining the high spectral resolution of the present instrument would be of great value. This could be accomplished by using two or more spectrographs rotated with respect to each other, by forming crystal

optical components through the careful shaping of the crystal slabs, and by analyzing with a crystal the image formed by an x-ray microscope. Second is the relative timing of the emission of the seed-gas x rays and the fuel burn. It appears that a crystal spectrograph (without a slit) could be coupled to an x-ray streak camera to obtain temporal resolutions on the order of 15 ps. This would allow experimental confirmation of the computer implosion simulations that form the basis for our confidence in the argon line imaging technique.

Key words: alpha scattering; argon—x-ray emission; Argus laser system; Fresnel zone plates; imaging techniques; inertial fusion; inertial fusion targets; ion density; ion temperature; neutron activation; spectrographic analysis; x-ray diffraction; x-ray images.

Notes and references

1. A detailed description of neutron activation and its use as a density diagnostic for fusion targets appears in the *Energy and Technology Review* for January 1980 (UCRL-52000-80-1), p. 10.
2. For a description of the zone-plate camera and zone-plate-coded imaging of thermonuclear burn, see the *Energy and Technology Review* for January 1978 (UCRL-52000-78-1), p. 1.
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Suppose the oil stops . . .

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Continued turmoil in the Middle East makes a complete cutoff of imported oil supplies from that region a possibility that must be considered. If a major oil cutoff occurred, it would cause disastrous short- and mid-range consequences to our economy. Drastic conservation measures would help to stretch the remaining supplies but only enough to cover about half of the shortfall. Efforts to produce significant effects by introducing other energy technologies and supplies involve long lead times and therefore cannot be effective in the short term. Foresight and initiative will be required if we are to develop effective coping strategies beforehand. Our purpose in this article is to estimate the magnitude of the maximum shortfall, to identify the major short-term actions possible in response to such a crisis, and to point out some longer range actions to complete our recovery.

For the past several months our Energy and Resource Planning Group has been evaluating the Mideast situation, the credibility of a complete oil cutoff, its possible effects on our economy, and the priorities and roles of energy research and development in this context. The work is still in progress, but enough has been done to justify a preliminary report.

It is clear that continued dependence on oil imports poses a growing threat to U.S. economic welfare. The stability of the Middle East is rapidly declining,¹⁻⁸ largely as a result of the individual and interlinking effects of Islamic resurgence (not only in Iran but throughout the region), the Arab nationalist movements, the continuing Palestinian refugee problem, and Soviet interference and now open aggression in Afghanistan.

In the past, the primary stabilizing influences in the Mideast were

Saudi Arabia and Iran. Recent events in Iran have left Saudi Arabia as the major Mideast nation sympathetic to U.S. and Western interests. However, instability in Saudi Arabia is increasing. Open rifts are occurring in the ruling family, Saudi funds are reported to be disappearing into private foreign bank accounts, and reports of attempts to overthrow the government continue to surface (11 attempts in the past 2-1/2 years.) One of the most widely publicized of these revolts was the recent seizure of the Great Mosque at Mecca as part of an attempt to split off western Saudi Arabia and convert it to a Hedjazi state.

There appears to be little the U.S. can do to improve the situation. The first oil embargo in 1973-74 revealed our vulnerability, and subsequent developments continue to show that our influence on events in the Middle East is tenuous at best.

With this as background, the worst-case scenario our planners envision is that the oil production in the region could stop. The price of oil could soar to over \$100 a barrel, roughly triple its present price, and there would be intense political and diplomatic pressure on the U.S. to stay out of world oil markets. The political and economic effects worldwide would be comparable in magnitude to those of World War II.

Our economic dependence

The world crude oil and natural-gas-liquids production rate in 1978 (excluding that of the Soviet-bloc nations) was 50 million barrels a day (MBD). Figure 1 shows graphically how this production was distributed, with roughly 40% (20.9 MBD) coming from the Middle East.⁹ Also shown is the distribution for the first eight months of 1979, the latest period for which

complete statistics are available, with proportionate amounts relatively unchanged.

Of this 50 MBD, the U.S. used 16.7 MBD. About 51% of this oil came from domestic production, leaving 8.1 MBD from imports, with 75% from non-OPEC sources. On the surface, therefore, it would appear that a complete cutoff of Mideast oil would curtail the U.S. supply by only about 12%, a painful but not necessarily disastrous adjustment.

We are, however, tied to 20 other nations by the International Energy Agency (IEA) agreement to share the effects of any oil shortfall equitably, regardless of the source. Together the signatories to this agreement import about 23 MBD (1978), and the Mideast exports

about 21 MBD of which 17 to 19 MBD is exported to the IEA countries. Hence a complete cutoff of Mideast production would result in a 74 to 83% cut in imported oil to each signatory. Our share of that cut would be 6 to 6.7 MBD, or 36 to 40% of our total oil use for 1978. For a country with no domestic oil, the cut would be 74 to 83% of its total consumption.

Short-range tasks

The first task under such a scenario is to assess where we use oil and where we can afford to cut consumption. Figure 2 is a diagram of 1978 energy flow for the U.S., showing the sources of energy (left) and the use categories (right). From such a diagram we can begin to see where most of the oil goes.

Table 1 summarizes the end uses of U.S. oil in 1978, as shown in the energy-flow diagram. The largest use, 53%, is for transportation. Within this sector, as shown in Table 2, the private auto uses about half of this amount. Hence, steps to improve the efficiency of cars or to limit their use are among the most effective measures we can take.

One such program is already in effect, a law mandating a 27.5-mpg average gasoline mileage for new cars by 1986. Already, some of the

newer cars are lighter and more compact, with improved fuel-efficient engines. As older cars retire and these more efficient cars take their place, the savings are estimated to reach 0.5 MBD by 1982, 0.7 MBD by 1985, and 1.4 MBD by 1990.

The other immediate way to save oil in the transportation sector is to reduce the miles driven. Figure 3 indicates the proportions of the various automotive uses, showing that savings are possible

Table 1 *End uses of oil in the United States in 1978.*

	MBD	%
Transportation	9.4	53
Residential and commercial	3.3	19
Non-energy	1.8	10
Electricity generation	1.4	8
Industrial	1.4	8
Export	0.3	2

Fig. 2 Energy flow in the United States in quads (2.12 quads = 1 MBD—millions of barrels of oil per day—equivalent) in 1978, the most recent year for which complete statistics are available. Energy inputs are on the left, energy use categories are on the right. Transportation absorbs more than 50% of the total supply of

petroleum and rejects over 75% of what it consumes. Emergency efforts to conserve oil would start with limiting the use of cars and with improving their efficiency. Together these measures might save as much as 1.2 to 1.6 MBD equivalent if put into effect immediately, with longer range savings of up to 2.1 to 2.5 MBD.

through increased reliance on buses and vanpools for commuting and by a drastic reduction in social and recreational driving.¹⁰ Both of these measures could be mandated in an emergency situation, and together they might save the equivalent of 0.7 to 1.1 MBD.

The residential and commercial sector is another significant use category, but it is harder to estimate the net effect of specific conservation measures. However, it is estimated that we can save about 60% of the energy consumed in residential uses, as indicated in Fig. 4.¹¹ Applying this factor to residential and commercial energy consumption, we estimate a total potential saving of about 2 MBD, with about 1 MBD in the short term.

A study at Oak Ridge National Laboratory¹² indicates that some oil could be saved by operating nuclear and coal-fired generating plants at full capacity and exporting their surplus power to areas served by gas- and oil-fired generators. The gas saved could then be used in industrial processes that now burn oil, for further oil savings. Such measures could be adopted almost immediately, and the oil saved would be about 0.4 MBD.

The economic impact

Combining all the immediate savings (those that could take effect within the first few years) as shown in Table 3, we arrive at a total of 2.8 MBD. The possible total shortfall is 6 to 6.7 MBD, however,

and the resulting net shortfall of 3.2 to 3.9 MBD would result in a severe economic shock.

Figure 5 shows two separate estimates¹³ of the change in gross national product (GNP) as a result of diminished oil supplies. A net drop of 3.4 to 4.1 MBD could result in a loss of about \$80 to 140 billion (1972 dollars) or 6 to 10% of the GNP. Such a loss would be the worst economic reversal the nation has suffered since the depression of the 1930s.

Longer term emergency measures

Some actions would be of little help in an emergency situation because they take longer to produce results, but if begun

Table 2 Estimated percentages of energy use in the transportation sector in 1978.

Automobiles	54.3
Trucking	22.5
Airplanes	8.9
Railroads	3.6
Other	10.7
Total	100.0

Earning a living

Family business

Education, civic, religious

Social and recreational

Other

Fig. 3 Relative amounts of various use categories for private automobiles. The largest category is work-related driving, mostly for commuting, and the second largest is social and recreational driving. Significant savings in oil dependence could be achieved by expanding the use of carpools, vanpools, and public transportation, and by curtailing social and recreational driving. In an emergency situation it is estimated that the total savings from such measures might be the equivalent of 0.7 to 1.1 MBD.

beforehand they could make a substantial difference. Among these are conversion of oil- and gas-fired steam and power plants to coal, extension of natural-gas distribution into areas that now depend on oil-fired furnaces, expansion of the electrical network to make possible more extensive fuel switching, and accelerated construction of coal and nuclear power plants.

For example, the ORNL study mentioned above also points out

that 40 to 50% of oil-fired industrial steam generation could profitably be converted to coal, potentially saving over 1 MBD. This option would also save money, making the change doubly attractive to industry. It would, however, require a redefinition of air quality standards.

There would also be substantial future benefits from extending natural gas distribution networks into areas where oil is the principal fuel for heating space and water.

Table 3 Emergency actions that could be taken in a crisis and the amounts of oil they might save in the first few years (in millions of barrels per day).

More efficient cars	0.5
Increased use of ridepools, public transportation	0.9
Reduced residential use	1.0
Increased nuclear and coal use	0.4
Total	2.8

Fig. 4 Reductions in energy use possible in a typical 1200-ft² house in Northern California requiring 3000 degree-days of heating. Although these estimates apply directly only to a house heated with gas, similar measures applied to an oil-heated house should produce similar results. Furthermore, a reduction in electricity consumption indirectly saves oil used to generate electricity. When these savings are extrapolated to the entire country and converted to MBD equivalents, we estimate that a short-term saving of about 1 MBD is possible, with longer-term savings of up to 2 MBD.

Fig. 5 Two estimates of annual loss of gross national product (GNP) in billions of dollars as a function of oil-supply shortages. An uncompensated loss of 3.4 to 4.1 MBD of oil, the likely impact of a complete cutoff of Middle-eastern oil for which we were unprepared, would result in a drop in the GNP of 6 to 10%. This represents an economic setback comparable to the Great Depression of the 1930s.

The gas for these uses would come from the industrial applications that had converted to coal. The potential saving is about 1.0 MBD, but the time span for completion is unknown.

Expanded use of electricity—generated from nonpetroleum sources—for space and water heating is another opportunity for saving, although it is hard to estimate exactly the impact it might have. Existing electric generating plants would need to be augmented considerably by accelerating construction of nuclear and coal plants that are already permitted.

The total of such savings at the end of five years might amount to 0.9 MBD from the expanded utility interlink system, 1.0 MBD from the expanded gas-distribution network, possibly 1 MBD from the increased residential and commercial conservation measures previously mentioned, 0.7 MBD from more efficient cars and more widespread use of public transportation, and 1 MBD from the shift to gas for industrial steam generation. The total, including the earlier savings

from immediate emergency measures, would amount to 7.2 MBD. Since the anticipated shortfall for the worst case is 6 to 6.7 MBD, if the oil cutoff came after these strategies were in effect, the economic impact could, over the long term, be greatly reduced (Fig. 5).

Actions for the mid range

In the mid range (3 to 10 years) several technological solutions could make a significant difference in our future consumption of oil. Research on these technologies is essentially completed, but, for one reason or another, they have not yet been commercialized. None of these can have any significant effect immediately because they require time for construction or for market penetration, but they could all soften the impact of an oil cutoff later on. Even more important, they will provide the means for eventual replacement of oil as a major energy source.

Electric vehicles have been produced that would be quite adequate for short-range driving. Using an advanced lead-acid battery, the General Electric-Chrysler electric vehicle has a range of 75 miles and can accelerate from 0 to 30 mph in 9 s. The battery can be recharged overnight, when the demand for electricity is lower and when the car

would not normally be in use. If such a vehicle were mass-produced, its price is estimated to be as low as \$6,000 (1979 dollars). If charged with electricity at 5¢/kWh, over its life cycle it would be competitive with an ordinary car operating on gasoline that cost \$1.75/gallon, 30% over current rates. As better batteries become available, they could be substituted to improve performance and extend range.

One such possibility is the aluminum-air battery presently under development at LLNL.¹⁴ This battery provides the energy density needed to give an electric vehicle an acceleration and range equal to that of gasoline-powered cars. It will also be easy to refuel, simply by replacing its aluminum anodes, removing the spent aluminum in the form of alumina powder, and adding tap water. The alumina is identical to the feedstock for an aluminum plant and could be recycled directly. If the electricity for recycling the alumina came from coal-fired or nuclear generating plants, such cars would operate without burning any oil. We have established the feasibility of this aluminum-air battery, and an accelerated development effort could make it available within the next five years.

Another possibility is the hybrid vehicle, in which an electric system carries the low-speed and steady-speed loads and a gasoline motor takes over for sudden acceleration and for long trips. Our studies indicate that such a vehicle could offer performance nearly equal to that of present compact cars plus substantial savings in oil, provided

the electricity is generated by coal or nuclear energy.

Since it would take several years, in any case, to get enough such cars onto the road to save significant quantities of oil, it is important to start producing them as soon as possible. No one is likely to attempt this task, however, until a demand develops, and this would probably happen naturally only after the oil flow stops. One approach to market development in the U.S. would be for government agencies to convert a major part of their fleets to such vehicles. This would permit us to establish performance specifications and would provide the incentive to develop the manufacturing and service capabilities needed to serve this guaranteed market. An analysis of this concept is needed to develop a plan and to determine its effectiveness toward meeting the larger consumer demand that would develop in response to an oil shortage crisis or to continually increasing gasoline prices.

Another way to reduce our dependence on imported oil would be to increase our ability to make gasoline from other materials. It is possible, for example, to make synthetic gasoline from coal. However, the process is elaborate and requires a chemical plant of great size and complexity.

It is simpler and less expensive to heat oil shale to drive out its oil, which can then be turned into gasoline in a conventional refinery. Our oil shale resource is huge,

equivalent to an estimated 720 billion barrels of oil. If used at the rate of 5 MBD, an estimated upper limit of production, this resource would last for almost 400 years. Costs for mining and retorting the shale may turn out to be as low as \$15 to \$20/barrel for open-pit mining and \$20 to \$30/barrel for room-and-pillar mining.¹⁵

In view of all these favorable statistics, why is there no oil-shale industry? One answer lies in environmental impact problems, which are considerable but probably not insurmountable. An even more important factor, however, lies in the distribution of the resource. Since only about 6% of the resource is privately owned, the individual plots are too small for large production rates. Furthermore, the technology applicable to these small plots (room-and-pillar mining) is more expensive than the strip mining applicable to the much larger federally owned resource. In addition, the lack of a workable policy and plan for managing and developing the larger federal resources has prevented developments that are now technically and economically feasible. Thus, the barriers to large-scale oil-shale development are mainly institutional.

If federal lands can be made accessible in large blocks, and if government and industry can cooperate in an integrated

resource development, it would be possible to proceed. Such a device as a Piceance Basin Authority, for example, would allow large-scale integrated management operation and would provide an effective means for efficient coordination of federal responsibilities. We expect that, ultimately, production at 2 to 5 MBD could be achieved. While production and marketing can best be accomplished by private industry, government must provide the means for integrated development.

Summary

In discussing these many contingency plans we have concentrated first on those that could have immediate effects in a possible emergency and then outlined various other long-term emergency measures.

The need for eventual elimination of oil from the national energy diet is obvious, but it cannot be accomplished by conservation and enforced measures alone. We must change the energy menu by switching to fuels that are domestically abundant. For the

next 10 to 20 years, the only major realistic alternatives are coal and nuclear energy, despite the controversies over their use. There is more energy in our coal reserves than in the entire Mideast oil resource. Our supply of uranium is vast and secure. The technologies and industrial infrastructure for both coal and nuclear power are well established, the capital investment for nuclear and coal plants is about the same as for coal-liquefaction plants, and the total cost of new nuclear and coal power generation is less than the operating costs of existing oil-fired plants.¹² Hence even new oil-fired generating plants could profitably be replaced with modern coal or nuclear plants.

In the longer term, we must close the nuclear fuel cycle by reprocessing the spent fuel elements to recover plutonium. Advancing the breeder reactor system to the commercial stage would guarantee independence of the nuclear industry from foreign uranium supplies.

A number of additional strategies could make significant contributions 5 to 20 years from now. Some of these are on the verge of feasibility and need only a little further development; others involve long construction times. Nevertheless, since domestic oil production is declining and will eventually cease, such advanced projects play an important role in our national economy even without an oil cutoff.

Wind and solar power are attractive alternatives because they tap renewable resources. Both are intermittent, however, and can provide only limited amounts of energy in any one location.

In addition to the aluminum-air battery mentioned previously, another technology that might, with additional development, improve the energy balance is underground retorting of oil shale.¹⁶ Because existing surface-retort technology appears adequate for our short-term need, studies of *in situ* retorting methods can proceed at less than high priority.

Since natural gas is practically interchangeable with oil in many

heating and power-generating applications, a sudden drop in oil imports could put a severe strain on our reserves of gas. There are large deposits of coal too deeply buried to be mined economically. Research aimed at developing technologies for underground coal gasification promises to tap these deposits, offering a way to produce gas at lower costs and with less environmental impact.¹⁷ The gas from such processes could be burned directly or converted into methanol or synthetic gasoline to augment our reserves of natural gas.

This listing is not intended to be exhaustive, and other equally valid strategies exist. Also, we have purposely excluded such long-term strategies as the development of fusion power.

Limiting ourselves to the near term, however, it seems clear that if a political upheaval in the Middle East were to catch us unprepared, the sum total of all the immediately available strategies would fall far short of making up for the sudden drop in oil supplies that could follow. It is equally apparent that selected investments now, relatively minor compared with a potential drop in the annual GNP of 6 to

10%, could show a substantial return in restoring our independence and in softening the impact of a possible oil cutoff.

Key words: automobiles; coal; coal gasification; conservation; electric vehicles; electric batteries; energy—conservation; energy storage; flywheels; hybrid vehicles; nuclear power; oil shale; solar ponds; synthetic fuels; wind power.

Notes and references

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Past titles

Articles in the Energy and Technology Review have been organized into subject areas approximately corresponding to the Assistant Secretaries' areas of responsibility in the Department of Energy and to other funding agencies. We list those subject areas below along with references to articles and brief reports published within the last several months.

DEFENSE PROGRAMS

Inertial fusion

Density diagnosis of fusion targets by neutron activation (January 1980)

Heavy-ion-driven fusion (March 1980)

Measuring subkilovolt x-ray emissions with a soft-x-ray streak camera (April 1980)

Producing hollow glass microspheres for inertial fusion targets (March 1980)

Ultrasoother coatings for microsphere targets (April 1980)

Military application

Brief—Earthquake at LLL (March 1980)

Electric gun: applications and potential (February 1980)

Holographic interferometry and nondestructive testing (January 1980)

The evolution of massive stars and the origin of the elements (February 1980)

Studies of short-lived fission products (May 1980)

Supernova: the explosive death of a star (February 1980)

ENERGY RESEARCH

Materials sciences

Studying glass structure with laser-excited fluorescence and computer simulation (April 1980)

FOSSIL ENERGY

Hoe Creek No. 3: first long-term underground coal gasification experiment with oxygen-steam injection (May 1980)

Stabilizing in situ oil shale retorts with injected grout (March 1980)

NUCLEAR ENERGY

Laser separation of deuterium (January 1980)

RESOURCE APPLICATIONS

Controlling scale formation in geothermal brines (May 1980)