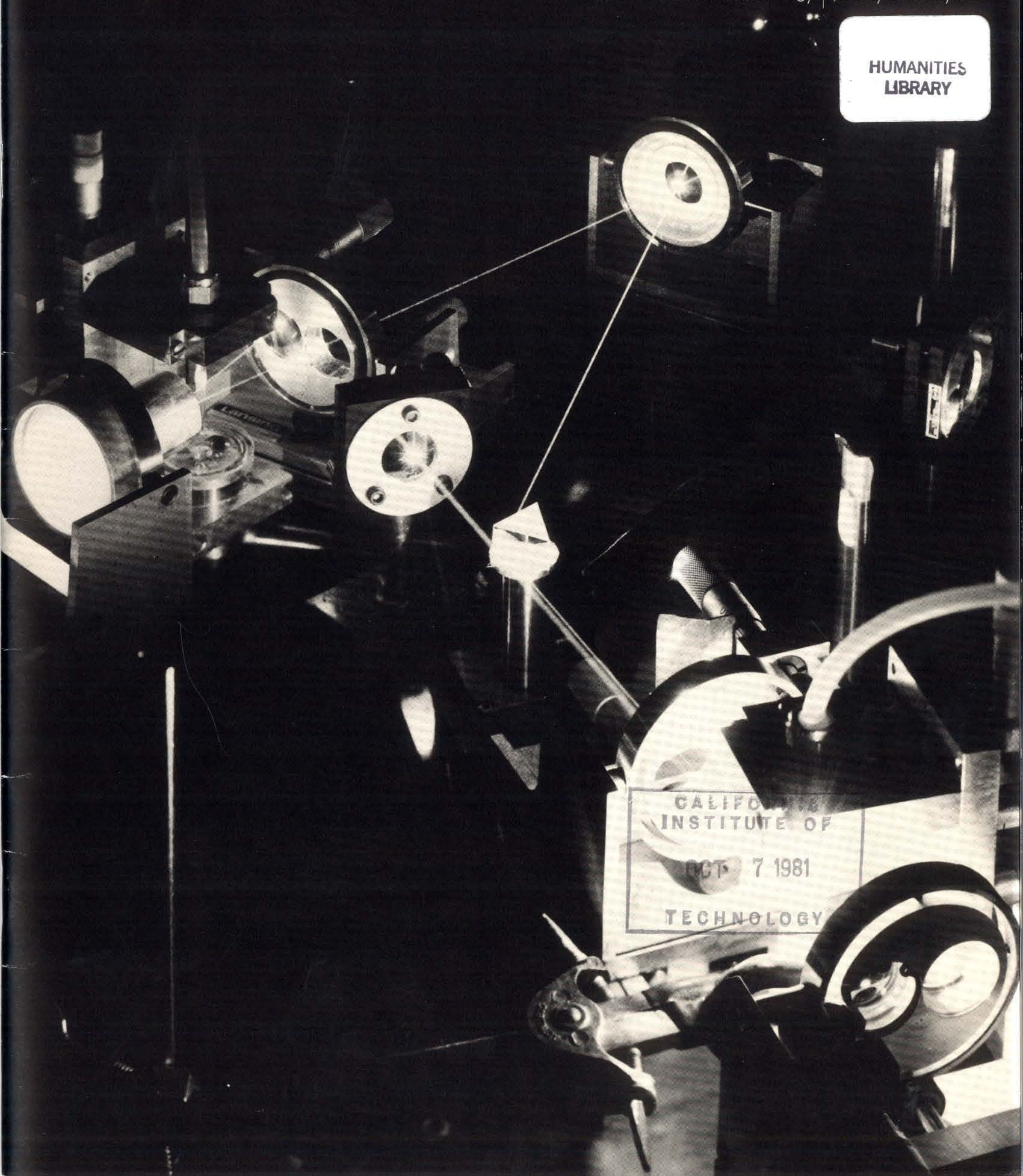
Engineering & Science

California Institute of Technology | January-February 1980



INSIDE FAIRCHILD

CLOSE-UP: SENIOR RESEARCH OPPORTUNITIES

The thrust of Fairchild's Research and Development efforts in the 1980's will be to develop submicron, very large scale silicon integrated circuits. Challenging projects involving all critical IC fabrication processes have been established to provide the technology required for these complex device structures. Existing processes will be upgraded, new ones will be developed, and detailed mechanism studies will be undertaken. Materials and process scientists associated with these projects will work directly with device engineers to develop state-of-the-art fine geometry circuits utilizing the most advanced processing equipment.

Career opportunities are available in the following areas.

Advanced Resist Technology

This project involves the investigation of state-of-the-art resist materials and processes in conjunction with fine geometry (VLSI) development programs. Currently available resist materials suitable for optical, electron beam, and x-ray lithography techniques will be evaluated and new resist materials will be developed.

These positions require a Ph.D. in Polymer Chemistry or equivalent and at least 3 years' experience in semiconductor resist and related technology.

Advanced CVD Technology

This program will involve the investigation of detailed mechanisms of chemical vapor deposition (CVD) processes. Of primary interest are polycrystalline silicon, silicon nitride and silicon oxide deposition processes. Individuals involved in this program will work with other high technology development groups in advancing the knowledge of CVD mechanisms and improving the properties of these films with respect to fine geometry device applications.

Candidates should have an MS or Ph.D. in Chemical Engineering, Chemistry, Materials Science or equivalent, plus at least 3 years' experience in semiconductor technology with emphasis on CVD processing.

Ion Implantation

This new program's goal will be to develop more precise means for measuring and controlling critical implant parameters such as dose, dose uniformity, beam purity and energy. Improved implant accuracy will be necessary for successful fabrication of coming generations of VLSI devices. Advances must be made in machine design and techniques for monitoring implants.

Candidates should have an MS or Ph.D. in Electrical Engineering, Physics, Materials Science or equivalent. Experience with ion implantation and/or semiconductor device fabrication is highly desirable.

Materials Analysis

This individual will perform routine analyses of electronic materials and integrated circuits, interpret results for customers and assist in the development of new analytical techniques as required by advances in VLSI technology.

This position will require an individual with a BS/MS in material science or equivalent. Prefer individual with a background in electronics.

Fairchild's Research and Development Laboratory is located in the Stanford University Industrial Park in Palo Alto, California. In addition to company sponsored projects, Fairchild scientists also participate in cooperative research programs with Stanford's Integrated Circuit Laboratory and other high technology organizations.

For immediate consideration, for these or other positions within Fairchild's Research and Development Laboratory, please send a detailed resume or letter of inquiry to Caryl Gates, Fairchild Corporate Staffing Office, MS 7-100E, 464 Ellis Street, Mountain View, California 94042.

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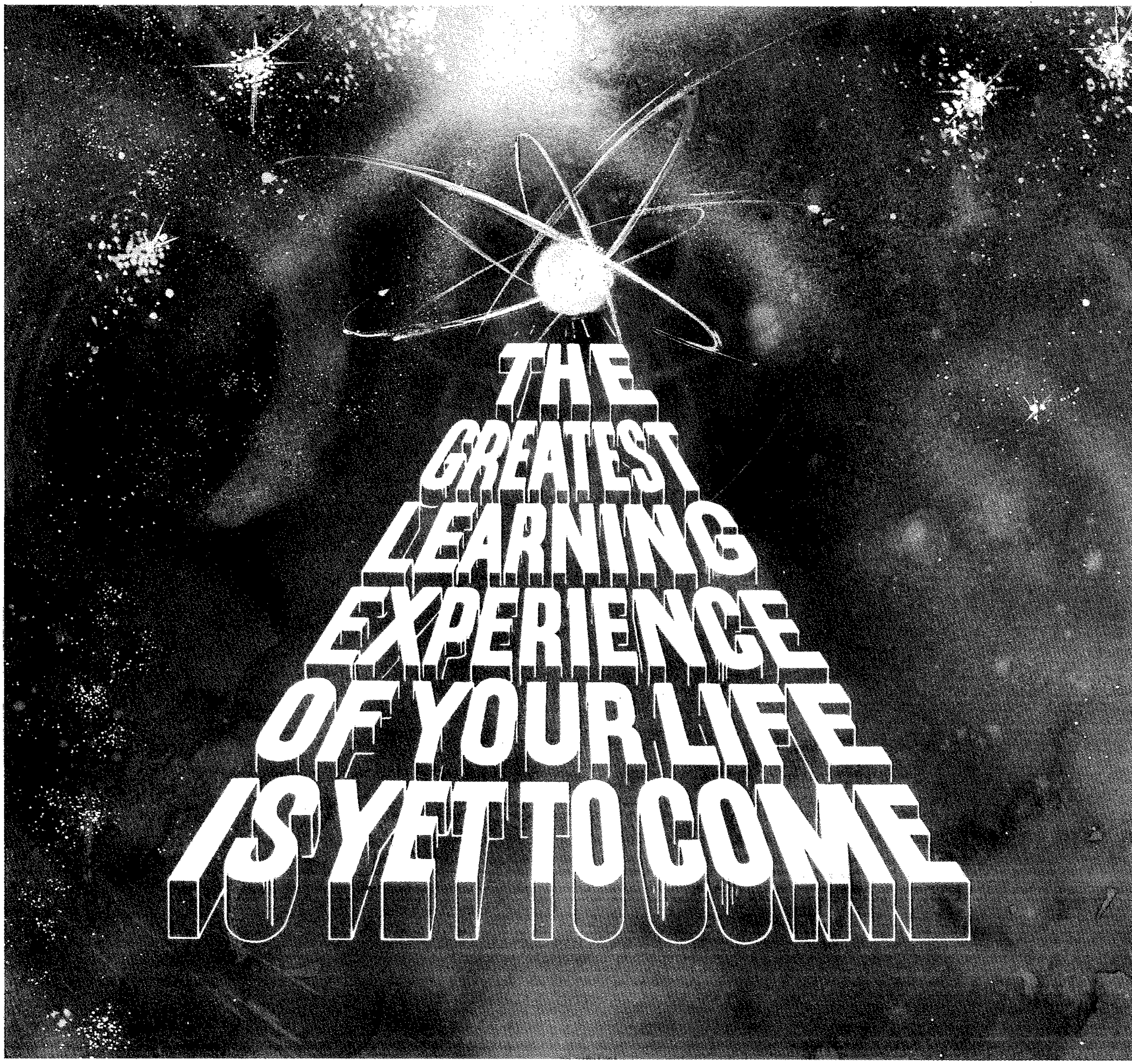

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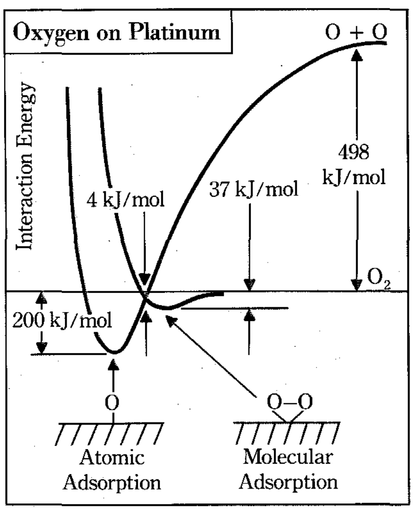
Engineering & Science

January-February 1980/Volume XLIII/Number 3

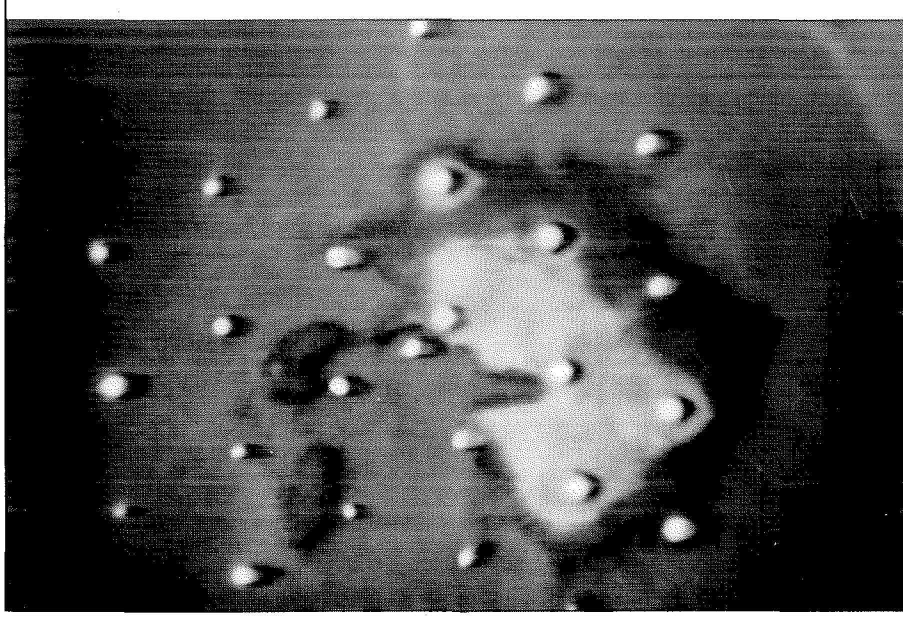
The Atomic Arrangement

In a recent experiment, scientists at the General Motors Research Laboratories studied changes in chemical bonding during the dissociation of oxygen molecules on platinum. Preliminary surface work has explored an interesting new phenomenon: the mechanism of oxygen dissociation over a wide range of temperatures.



A simplified schematic illustrating the reaction potential energy surface for oxygen-adsorption on a close-packed platinum surface.

An electron diffraction pattern which shows diffraction patterns from an oxygen-covered hexagonally close-packed platinum surface at 0° C.



UNDER what conditions will oxygen molecules dissociate into single atoms on a platinum surface? What is the mechanism for oxygen dissociation? Those are the kinds of questions that Dr. John Gland and his colleagues at the General Motors Research Laboratories are investigating to get a better understanding of the chemistry behind catalysis.

Their work has valuable practical implications for the automotive field, where catalysis is used to remove harmful emissions from automobile exhaust. Most cars built in the U.S. use catalytic converters filled with beads containing platinum to chemically transform carbon monoxide and unburned hydrocarbons into harmless CO_2 and water.

While it has long been known that catalysts are an effective way to convert these gases, little is known about precisely why and in what order the basic atomic reactions occur.

In seeking answers to these questions, surface chemists study the elemental composition and geometric arrangement of atoms in the first few atomic layers of the surface and the means by which atoms and molecules from the gas phase bond to the surface.

In his most recent work, Dr. Gland has been studying the adsorption and desorption of oxygen on platinum single-crystal surfaces. This is important because oxygen is the agent that must be adsorbed on the surface to react with carbon monoxide and hydrocarbons to convert them to CO_2.

The experiments were conducted in a stainless steel ultrahigh vacuum system equipped with an electron energy analyzer and a mass spectrometer. The electron energy analyzer allows one to measure the concentration and character of the oxygen adsorbed on the platinum surface. The mass spectrometer is used to measure the desorption of O_2 as the platinum surface is heated. Mathematical analysis of the desorption process allows one to characterize the chemical bond between the oxygen and the platinum surface.

In these experiments, the platinum surface is covered with oxygen at the extremely low temperature of −179°C (almost the temperature of liquid nitrogen) by exposing it to gaseous O_2 molecules. The oxygen remaining in the gas phase is pumped away, and then the desorption of oxygen from the surface is observed as the platinum crystal is gradually heated to 1000°C.

The oxygen was found to desorb from the surface in two distinctly different temperature regimes—part at −125°C and the rest at about 425°C. By using the oxygen-18 isotope, it was established that the low temperature desorption represents oxygen that was adsorbed on the surface in a molecular form while the higher temperature desorption corresponds to oxygen adsorbed in the atomic form. From an analysis of the desorption process, it was possible to establish the complete energetics. Oxygen molecules from the gas phase strike the surface and are weakly bound (37 kJ/mol). The adsorbed oxygen molecule can either desorb into the gas phase (37 kJ/mol) or dissociate into atoms (33 kJ/mol). The atoms are bonded very strongly (200 kJ/mol) to the surface.

FROM the desorption analysis, it was also possible to deduce the mechanism for the dissociation process. The interesting conclusion that results is that the formation of O atoms on platinum is a two-step process—oxygen is adsorbed in a molecular state and then dissociates to form atoms.

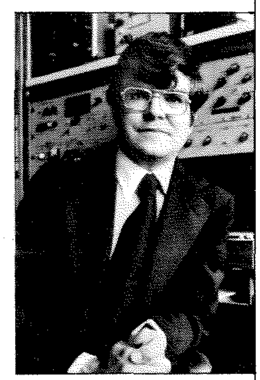
The GM scientists were most interested in learning how this adsorbed molecular species is bonded to the platinum surface. Fortunately, another technique was available to determine the bonding. The technique is called electron energy-loss spectroscopy and is quite new—there are only six or seven such instruments in the world. The measurements not only confirmed the existence of the adsorbed molecular oxygen but showed that it was bound by the transfer of two electrons from the platinum surface into the antibonding π_g orbitals of oxygen. "This was most exciting" said Dr. Gland, "because this is the first time that this type of oxygen bond has been observed on a metal surface.

"We're getting closer and closer to a more specific understanding of catalysis," says Dr. Gland. "The more we learn about simple chemical systems, the better we'll be able to control more complicated systems. That has excellent implications for protecting the environment."

THE MAN BEHIND THE WORK

Dr. John Gland, 32 years old, is a Senior Research Scientist in surface chemistry at the General Motors Research Laboratories. He heads a group of 7 investigators, 4 with Ph.D.s, all involved in work relating to the basic surface chemistry of catalysis.

A graduate of Whittenberg University in Ohio, Dr. Gland received his Ph.D. in physical chemistry at the University of California, Berkeley, in 1973 and joined the General Motors staff that year.



Dr. Gland comments: "I came to GM Labs because I wanted to get in on the ground floor of an exciting new field. The atmosphere here is very open, with lots of cross-pollination among departments. With several hundred people with Ph.D.s here, we've got a lot of human resources to draw on in all the basic sciences.

"Typically, management defines a broad problem, then we're free to tackle the solution in any way we choose. They give us the freedom, equipment and support to get the job done correctly."

In addition to his research, Dr. Gland enjoys backpacking in Wyoming and in the Sierra Nevada Mountains in California.

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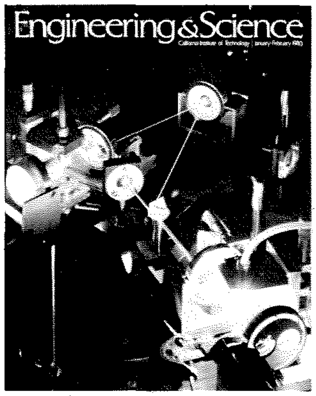
In This Issue



Laser "Alchemy"

On the cover — a view of the laser apparatus and beams of light produced in the laboratory of Ahmed Zewail, associate professor of chemical physics at Caltech. A dye jet stream makes the lasing medium in the cavity. Note the coherent laser beam between the prism (center) and the mirror (below the word "Institute") in comparison with the incoherent emission of the dye molecules at lower right.

Ahmed Zewail

Lasers are the tools with which Zewail carries on the research he described in a lecture at the 1979 Research Directors Conference sponsored by Caltech's Industrial Associates. "Laser Selective Chemistry" on page 8 is adapted from that talk.

In addition to his research with lasers, Zewail has done some exciting work in developing a "multiple-dye planar solar concentrator" that will greatly increase the efficiency of silicon solar cells that convert sunlight into electricity. He was recently awarded a $35,000 Dreyfus Teacher-Scholar grant for "exceptionally promising young faculty members who combine an interest and a demonstrated ability in teaching and performing research."

In some of his lectures, whether the subject is laser chemistry or solar energy, Zewail also has an amazing ability to get in a plug for Egypt, usually saying something about chemistry being "an old field known since the days of the ancient Egyptians" or about Egyptians being the first to worship the sun god Aton. As you might have guessed, Zewail was born in Egypt, and received his BSc from the University of Alexandria. After obtaining his PhD from the University of Pennsylvania, he was a research associate at Berkeley and has been at Caltech since 1976.

Outlook on Energy

Bringing the realities of the energy situation home to the citizens of this country is something of a problem in continuing education — and it is one that the Caltech community is involved in at a number of levels, including that of the Board of Trustees. The Institute is fortunate that several members of that Board are, because of both opportunity and experience, particularly well qualified to speak knowledgeably on the question. This made it possible and appropriate to assemble five of them into a blue ribbon panel to speak informally about various aspects of the energy problem at the Board's annual three-day fall meeting in October. In "World Energy Perspectives" on page 14, *E&S* presents adaptations of the panel's talks.

The members of the panel itself were Robert O. Anderson, chairman and chief executive officer of Atlantic Richfield Company; Robert S. McNamara, president of the World Bank; William R. Gould, president of Southern California Edison Company; Dean A. McGee, chairman and chief executive officer of Kerr-McGee Corporation; and Simon Ramo, director, and chairman of the science and technology committee of TRW Inc.

At the conclusion of the panel's presentation, Caltech President Marvin Goldberger invited questions and discussion from the floor. A number of trustees responded, including, in particular, William M. Keck Jr., who has been active in the petroleum business for more than 50 years and is currently a director of the Superior Oil Company.

Mr. Keck reacted to the presentations of the panelists by recounting several specific problems of government regulation and current consumer views toward such producing companies as his. He also commented on the potential for development of oil shale deposits in the western states, the potential for coal, and the difficulties of bringing energy supplies from source to market.

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January-February 1980

Laser Selective Chemistry

A New Challenge for Chemists and Physicists

by Ahmed Zewail

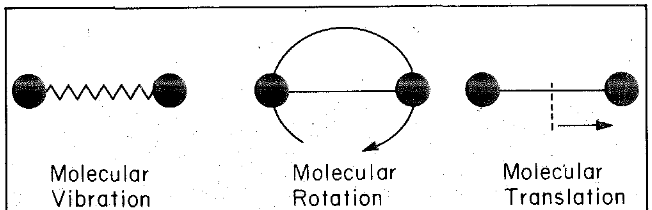
How can molecules be cracked selectively with lasers, and what happens to them under heavy doses of laser radiation?

One of the main goals of chemists is to understand the "alchemy" that leads to the cracking and building of molecules. Approaches toward this goal are numerous and involve a working team of organic and inorganic chemists and chemical physicists. For centuries large molecules have been put together and taken apart using conventional organic synthesis or photochemistry.

To achieve total organic synthesis, an organic architect designs the different parts of a desired molecule and then joins these blocks, made of atoms and bonds, chemically. A photochemist, on the other hand, is interested in taking apart the blocks by adding energy in the form of light to break the bonds. This bond breakage is limited by statistical thermodynamic laws. Furthermore, a conventional light source excites all bonds indiscriminately — with no selectivity. With lasers we hope to bypass these laws and to build and crack large molecules selectively — to break molecules precisely where we want to break them. Intellectually this is a challenging problem to understand, and, if we succeed, laser selective chemistry will have application in various areas of applied chemistry and perhaps in medicine.

Laser chemistry involves two basic questions: *How* can we crack molecules selectively with lasers? And *what* happens when molecules are subjected to heavy doses of laser radiation? Before discussing these questions, perhaps it will be useful to explain a few things about both molecules and lasers.

Molecules are made of chemical bonds holding atoms together. In large molecules (that is, those with more than two atoms) the bonds are weak or strong depending on the atomic constituents and on the shape of the molecule. When the atoms take on energy, by heating for example, the bonds vibrate according to well-known rules in physics. In addition to vibrations, the molecules can convert the input energy to translational motion, changing their position, and/or to rotational motion, which causes the entire molecule to rotate in well-defined steps. It takes different amounts of energy to produce these different degrees of freedom (vibrational, translational, and rotational) — the vibrational energy is greater than the rotational energy. Because the molecule accepts the energy in a

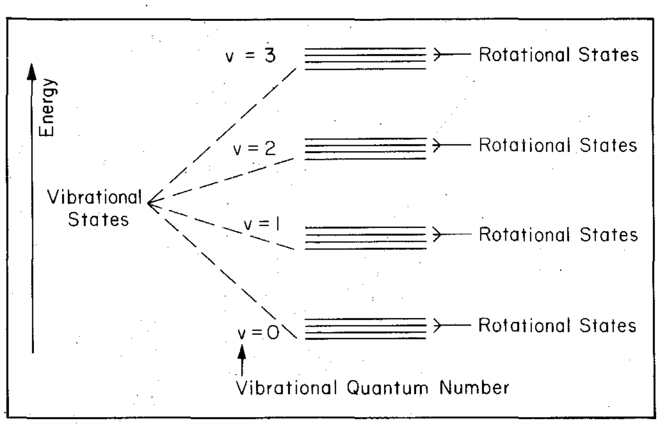


A diatomic molecule consists of two atoms connected by a bond. Energy supplied to the molecule is converted to vibrational, rotational, or translational motion.

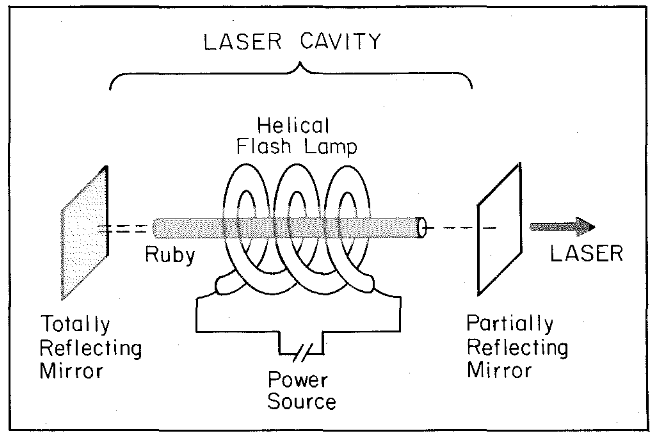
quantized or discrete way, chemists describe vibrational and rotational events using states diagrams with the vibrational and rotational energies dictated by the laws of quantum mechanics. These vibrational and rotational states can be probed by using different light sources, but it is vibrational energy we are mainly interested in here.

The weaker bonds of a molecule are more vulnerable to breakage when vibrating; when they do break, the chemical reaction proceeds. Unlike conventional light sources, lasers can, in principle, heat certain bonds in the molecule and leave all others cold, enabling chemists to direct a chemical reaction by causing certain bonds — not necessarily the weakest ones — to break. But how do we go about such selective heating? To answer this question we must first know what goes on inside these large molecules — how the bonds "communicate" with each other, how fast the heat (or energy) spreads among the bonds — or the different vibrational states. We must also understand why certain lasers can do the job while others cannot. In other words, we must still resolve some problems standing in the way of a happy marriage between lasers and molecules — laser chemistry.

The word "laser" is an acronym for light amplification by stimulated emission of radiation. A basic laser apparatus consists of a lasing medium and two mirrors, one of them totally reflecting and the other partially reflecting and partially transmitting. The lasing medium or material can be the atoms, molecules or ions in a gas (for example, argon ion laser) or a solid (for example, ruby in a solid state laser). When these molecules or atoms are pumped into an excited state by a flash of intense light, or sometimes by another laser, the process begins: One excited atom spontaneously emits a photon, which hits another excited atom, causing it to emit another photon of the same frequency and direction. While photons emitted in wrong directions will leave the lasing medium, those perpendicular to the mirrors will be "trapped," bouncing back and forth between the mirrors until all the waves of emitted radiation are aligned in "sync" with each other (with the same frequency and direction). Thus an intense, coherent beam of light — the laser — is born and released through the partially transmitting mirror at one end.

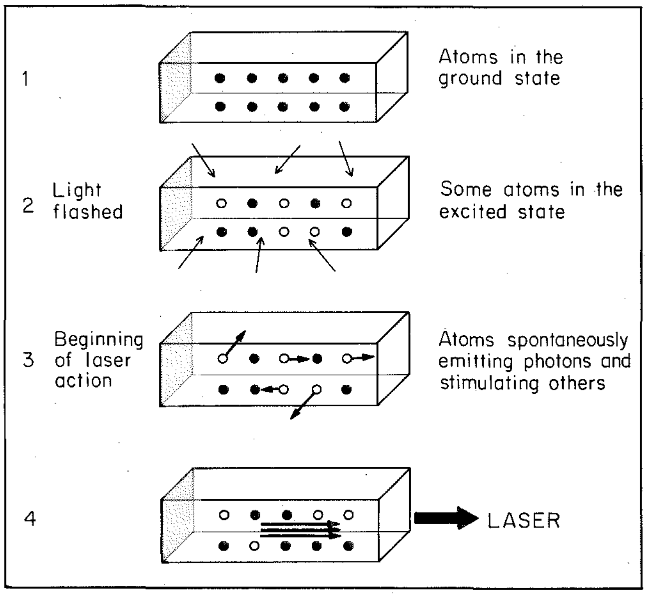


According to the laws of quantum mechanics, energy is given to a molecule in discrete steps or vibrational states. The quantum number, v, equals 1, 2, 3 . . . as the deposited energy is increased. Since rotational energy is less than vibrational (less energy is needed to turn a molecule than to stretch its bonds), each vibrational state contains many rotational states.



In this typical laser device, the lasing medium (ruby) is encircled by an intense light flash that excites the atoms so that they emit photons. The photons emitted in a path horizontal to the axis of the lasing medium bounce between the mirrors on either end of the laser cavity and are released as a laser beam through the partial mirror at right.

Lasers have many nice properties that are useful in numerous areas of research. They are monochromatic, that is, all the photons have very nearly the same frequency. In contrast to "white" radiation, such as a flash of ordinary light, which contains all colors at wide frequency ranges (for example, blue to red), laser radiation is selective and has a narrow band width. For example, a tunable dye laser, in which the lasing medium is a dye solution instead of the ruby in the diagram above, can produce radiation at 6000Å with a resolution (or band width) of better than 10^{-4} reciprocal centimeters (cm^{-1}). This is equivalent to an energy of approximately 10^{-8} electron volts or to a temperature of approximately 10^{-4} Kelvin. For contrast, a tungsten bulb has a "resolution" of about 10^{4} Kelvin. In the United States, primarily at the National Bureau of Standards and the Massachusetts Institute of Technology, and in the Soviet Union, extremely small laser band widths of less than 50 kilohertz have been achieved. This property enables scientists to conduct optical spectroscopy and laser chemistry with very high resolution — the resolution of radio frequency or microwave spectroscopy. Thus rotational and vibrational states of molecules *can* be excited



With dots in a box representing the atoms of the lasing medium, figure 1 shows unexcited atoms. When light is flashed, some atoms become excited (open dots — 2), emit photons (arrows — 3), and stimulate others to emit more photons. Some of these leave the system, while those in a horizontal direction trapped by the mirrors bounce back and forth to form a laser radiation.

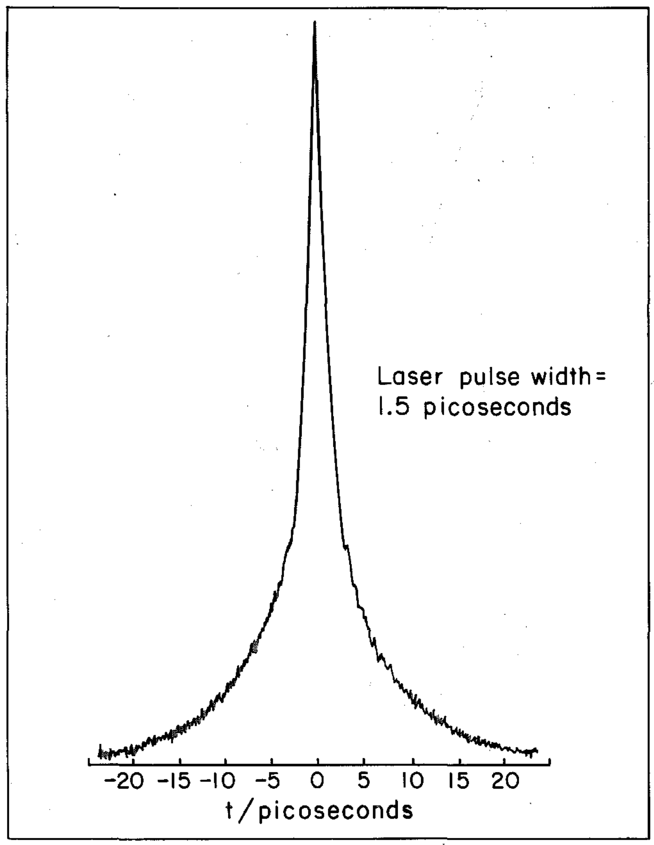
selectively, and indeed many laboratories around the world are involved with laser spectroscopy of rotational and vibrational states in molecules.

Other advantages of the laser are its high intensity, its capacity to propagate over long distances, and its variable time duration. In laboratories today a burst of radiation carrying 10^9 watts per square centimeter at, say, 6000Å can be generated routinely. The burst, which travels with the speed of light, has a time resolution of better than a trillionth of a second (10^{-12} or picosecond). These ultrafast light sources (although perhaps in five to ten years picosecond pulses will be considered comparatively long in duration) open the door for the study of the ultrafast processes in molecules. Selective bond cracking may require ultrafast lasers for reasons I will cover later. Such picosecond pulses have been generated at Caltech to study molecular and chemical processes and reactions.

Lasers may induce the chemical reaction selectively or non-selectively. When a large molecule is excited in a non-selective way, the different bond vibrations "communicate" with each other so that the energy is distributed statistically among them. In effect, the molecule is heated uniformly, and equilibrium is reached among all vibrations in accordance with the laws of statistical thermodynamics. The reactivity of the molecule under these conditions has been described by a well-known theory advanced by Rice, Ramsperger, Kassel, and Marcus (RRKM). In some sense, by using selective laser chemistry, we hope to deviate from the RRKM limit and achieve a highly non-statistical bond cracking. This objective may be gained in either or both of two ways: by slowing down the communications among certain vibrations, or by breaking one bond so fast that there is no time for communication among the different vibration bonds of the large molecule.

The communication process can be illustrated by using zigzag lines resembling springs (which stretch with vibration) to indicate the bond vibrations between the atoms. The "springs" of a polyatomic molecule such as benzene are the bonds connecting two carbon atoms or carbon and hydrogen atoms, etc. According to simple laws, there are 3N-6 vibrations (where N is the number of atoms); since the benzene molecule has 12 atoms, 6 carbons and 6 hydrogens, there are 30 different vibrations.

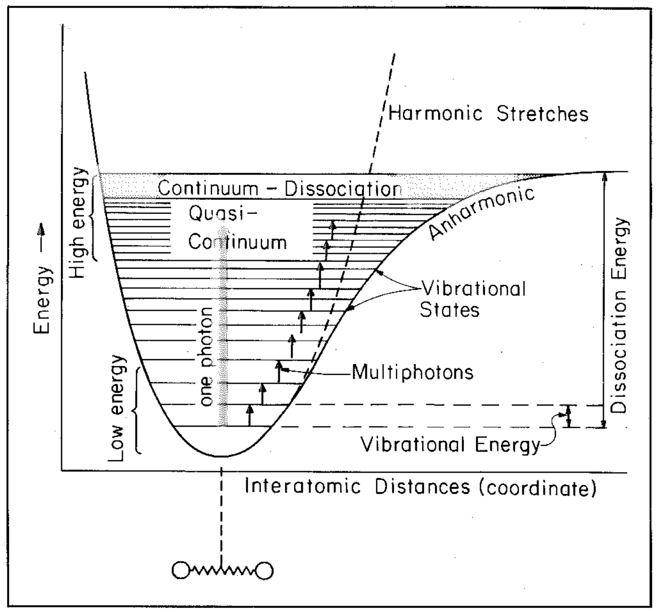
In a diatomic molecule, on the other hand, there is only one vibration (or one spring). If the diatomic molecule is



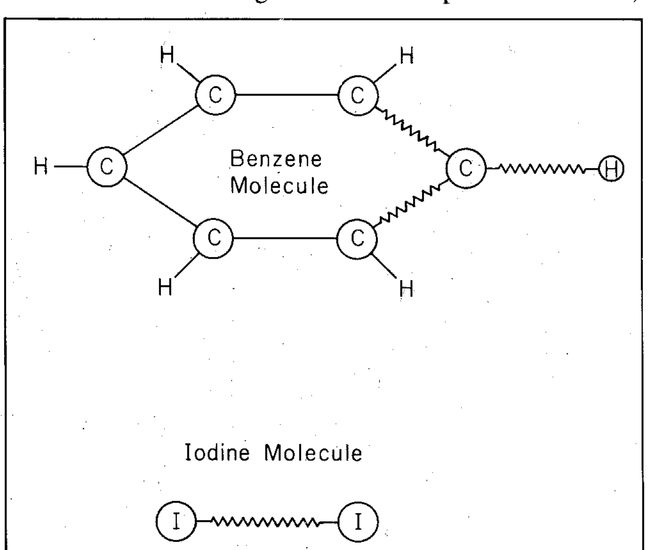
This optical radiation of picosecond laser pulse with a pulse width of 1.5 picoseconds and wavelength of about 6,000 Å was obtained at Caltech. Even smaller pulses may be necessary to break molecules selectively.

given a relatively low energy, the bond vibrates in a harmonic way (like a harmonic oscillator or regular pendulum motion). As the energy increases, the vibration becomes anharmonic, or irregular. The motion in the low- and high-energy limits can be visualized in terms of a potential energy surface — energy versus vibrational displacement — or in terms of the vibrational states discussed earlier. The more energy is added, the farther the bonds stretch in either direction; the wider the stretch expands, the more possibility of irregular motion or anharmonicity. Because of anharmonicity, in a polyatomic molecule vibrations that are close together can couple to each other (communicate their energy). This happens particularly at high energies, where there are numerous vibrational states, or *combinations* of many vibrations. For example, for about two electron volts of energy in the benzene molecule there will be about one hundred million states per reciprocal centimeter (cm^{-1}). At these very high energies the vibrational levels are so close in energy that they form what is called a *quasi-continuum* of levels. The quasi-continuum, which represents a density of vibrational levels — or energy states — that are so close together they are practically indistinguishable, may or may not help us achieve selectivity. It will depend on how fast the deposited energy in a given bond spreads or randomizes to all other bonds.

Experimentally, selective laser stimulation of vibrational states in molecules can be accomplished by exciting the bonds with a single photon or with multiphotons. In the former we provide the molecule with the required energy for dissociation in a single shot. In multiphoton excitation,



If you consider the horizontal axis in this diagram of polyatomic molecular states as the length of a "spring" or vibrating bond between atoms, you can see the spring stretch to the breaking point (dissociation) as the energy is increased. Higher energy also creates anharmonicity, or irregular vibration, shown by the curve veering to the right. Anharmonicity also causes coupling of vibrations, especially when there are many vibrational states close together in a quasi-continuum; this makes dissociation of the molecule possible through many low-energy photons (small arrows), which can "climb up" through the numerous vibrational states of the molecule to the dissociation level. The molecule can also be broken by a single photon (arrow) of the dissociation energy. In that case the photon is typically in the ultraviolet rather than in the infrared.



The six carbon atoms and six hydrogen atoms of the polyatomic benzene molecule are connected together by "springs" or bond vibrations. The diatomic iodine molecule has only one vibration.

however, the laser energy (frequency times Planck's constant) is much smaller than the necessary dissociation energy. But the many low-energy photons will be successively absorbed among the many vibrational levels until sufficient energy has been accumulated to dissociate the molecule. The quasi-continuum helps the "climbing up" process (through successive energy levels) because it contains many states that can match the energy of the low-energy or infrared photons. So even though the photon energy is much less than the dissociation energy, this mechanism does not violate the energy conservation laws of quantum mechanics simply because the molecule is immersed in a sea of infrared photons.

Visible and infrared single-photon excitation can be achieved through conventional sources of light and heat, such as flame, electric arc, etc., after passing the radiation through a frequency selector, or monochromator, to achieve high resolution. But the energy left after passing through the frequency selector is very small compared to laser energy with the same resolution, which is millions or even trillions of times greater. This makes lasers much more efficient than conventional light sources in the multiphoton process.

Here at Caltech our work has been particularly involved with the role of energy relaxation — the rate at which energy is distributed to other modes, or bonds, after being locally, or selectively, excited in one mode. In our laser group Joe Perry and Duane Smith, graduate students in chemistry, have investigated bond locality in the molecules naphthalene and benzophenone. Using single photons, we vibrationally excited the molecules to their C–H and C=O bonds as a function of energy, covering the low- and high-energy limits. The experiments were done on molecules frozen to 1.3 Kelvin, so that rotational and translational motions of the molecule were absent. Cooling also kept the quasi-continuum "out of the picture," since no molecules could be in that state before turning on the light source — at 1.3 Kelvin all molecules are in v=0.

According to the formula mentioned earlier in our discussion of benzene — 3N-6 — naphthalene vibrates in 48 different modes, while benzophenone vibrates in 66 modes. The C–H and C=O stretches are about 3,000 cm^{-1} and 1,700 cm^{-1}, respectively. Since the dissociation energy of the C–H bond in naphthalene is about 44,000 cm^{-1}, approximately 15 photons with the energies of the C–H mode are needed for the molecule to dissociate. To examine the C–H and C=O bond locality we measured (a) the spectra of the modes and (b) the relaxation time of the excited mode by all other modes in the molecule.

From our naphthalene and benzophenone experiments we found that:

1. The overtone spectrum (that is, the spectrum of v= 1,2,3 . . . states, where v is an index for the vibrational state — the quantum number) is a simple progression of C–H or C=O spectral bands (especially at high energies) with energies obeying the *simple anharmonic rule of diatomics*.

2. At about 15,000 cm^{-1} (about 1.9 electron volts) in the molecule, the stretches of C–H_α and C–H_β in naphthalene are distinct.

3. The relaxation time gets shorter as the energy increases in the C=O of the benzophenone molecule.

4. The C–H_α and C–H_β bonds in naphthalene have different relaxation times (.075 and .11 picoseconds) even when the other modes (sometimes called the "bath") are cooled to 1.3 Kelvin.

What do these findings mean? If we think of naphthalene's bonds as not communicating with each other, we could represent the molecule as simply the algebraic sum of the different diatomic bonds:

$$\text{naphthalene} = 4C-H_\alpha + 4C-H_\beta + \ldots \text{ etc.}$$

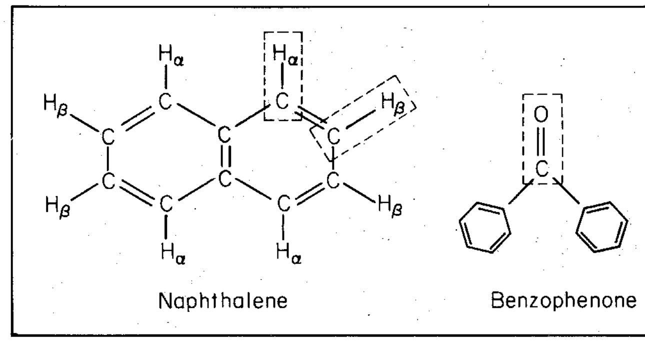
And in fact, experimentally, in both the naphthalene C–H stretches and the benzophenone C=O stretch, a simple relationship, like that in a diatomic molecule between the vibrational energy and the vibrational quantum number ($\bar{v}$), holds up very nicely and accurately.

Can we conclude from this that the energy is localized in the C–H or C=O bond? The answer is no. All it means is that our results are consistent with a local bond. But in order to prove the locality we need further evidence.

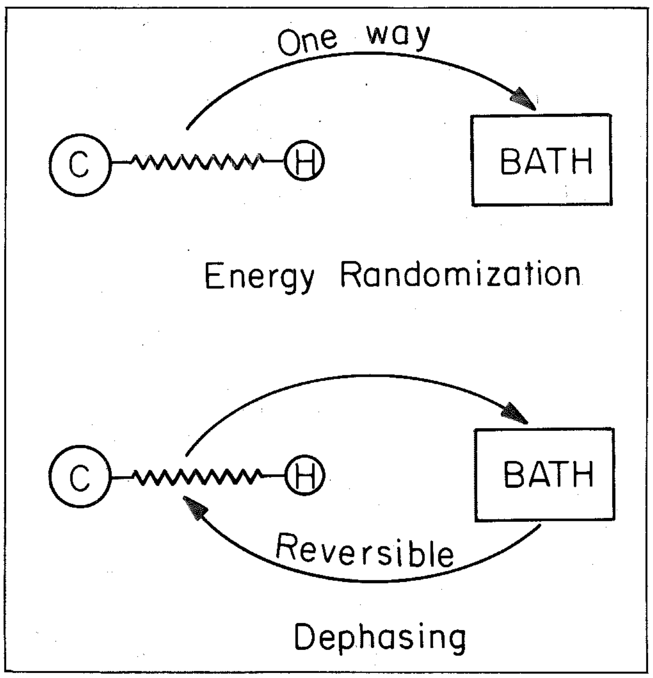
From our experiments we do know that the energy stays in the C–H bond for fractions of picoseconds or longer. Now we are faced with a dilemma: On one hand the spectra are consistent with a local bond picture, but on the other hand the relaxation time out of these bonds is ultrashort. Eventually lasers may be developed that can break a bond at this speed, but for the moment it might seem that we would have to give up.

However, there is another channel of relaxation that affects our previous measurement of relaxation time. The calculation of a relaxation time of subpicoseconds or picoseconds was based on the assumption of no thermal excitation in the bath at absolute zero and a one-way process of the selectively excited bonds dumping their energy irreversibly into the bath in a time T_1. But it's not quite that simple. In a distinctly different process called dephasing (T_2 time constant), a network of coherence may exist by which all the modes feel each other's existence.

For illustration we can think of the modes as dancers in a corps de ballet. If one dancer misses a step and gets out of phase with the others, she (or he) will cause a disturbance in the routine but will not affect the *number* of dan-



In Caltech research on bond locality, laser energy was focused on the C-H_α and C-H_β bonds of naphthalene and the C=O bond of benzophenone to determine whether these bonds could be excited selectively for a period of time before passing the excitation on to the molecules' other bonds.



When assuming no initial excitation in the bonds other than the one selectively excited, energy relaxation to the bath made of other bonds is a one-way process. However, a network of coherence may connect the vibrations and allow a continually reversible exchange of energy (dephasing). Both of these situations enter into the actual time measurement of relaxation.

cers on stage. Similarly, the C–H or C=O bonds can be out of phase (dephase) with other bonds without any net loss of energy. Physically this dephasing may then be visualized as a reversible transfer of energy back from the molecules in the bath as well as to them, and this must also enter into our calculation of the total relaxation time. For successful selective chemistry both T_1 and T_2 must be known; T_1 tells us how fast the deposited energy is flowing to all modes, and T_2 tells us what kind of lasers we should use.

What we do not know at the moment is the contribution of each of the relaxation times (T_1 and T_2) to the *measured* overall relaxation time. It may be that bond locality time is much longer than the .1 picosecond we measured — even long enough for us to get at it and break it with current laser technology. We also do not yet know how to describe theoretically the spectral shapes of high-energy transitions. This is in contrast to our rich knowledge about the spectra of low-energy states.

Our laser group is currently examining this point, focusing on the following three questions:

1. In the selective excitation of molecules by lasers, can we induce picosecond or femtosecond (10^{-15} or a thousandth of a millionth of a millionth of a second) laser chemistry?

2. If the selectively deposited energy is shared among all modes, is the distribution statistical?

3. Does the observed spectrum in the high-energy region reflect the locality of energy in bonds?

Put another way, we want to find out if there is such a thing as "permanent" bond locality. Basically, we would like to make the polyatomic molecule behave like a diatomic one, with precise mode-to-mode energy flow. Once we know the answers to these and to other remaining questions, we might be able to crack and build molecules selectively with lasers just as we can wreck a car or put it back together with the proper tools.

LASER SCIENCE AT CALTECH

With the interaction among its divisions, Caltech offers a particularly positive environment for probing the many aspects of laser chemistry. There are many faculty members here — in chemistry, chemical engineering, chemical physics, and applied physics — investigating, theoretically and experimentally, lasers and laser-matter interactions. In chemistry, Rudolph Marcus is interested in the behavior of molecules in the low-energy and quasi-continuum limits. Vincent McKoy is examining new theoretical implications for exciting molecules into the dissociation limit through electron-molecule scattering. And one of the leading authorities on the calculation of bond energies in molecules is William Goddard.

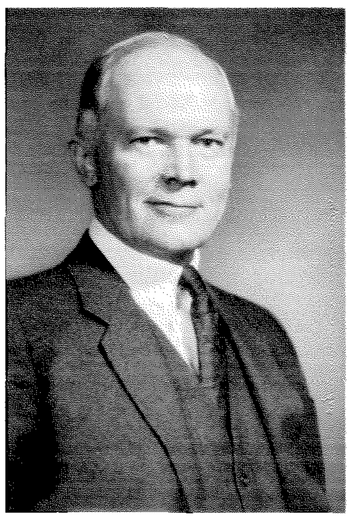
On the experimental side several groups are also involved. Henry Weinberg is studying molecule-surface interactions when the molecule is selectively excited into some vibrational states. Jack Beauchamp is investigating the dissociation of a number of molecules using infrared sources and ion-cyclotron-resonance spectroscopy. Vibrational excitation in diatomic molecules is being examined by Aron Kuppermann to learn about the influence of potential energy surfaces on chemical reactivity. Kenneth Janda is initiating a program to study such dynamical processes in a molecular beam, and Peter Dervan is designing the synthesis of a certain class of molecules that may localize energy better than others.

In electrical engineering and applied physics we also have some outstanding laser engineers and physicists. Among them are Amnon Yariv, William Bridges, and Fred Culick. Finally, in my own laser group we are trying to "shed some light" on the ultrafast processes that take place in molecules, using picosecond and ultra-high-resolution laser spectroscopy. □

World Energy Perspectives

Five members of Caltech's Board of Trustees discuss the current energy situation, how it happened, and some possibilities for the future

Robert O. Anderson
Chairman and Chief
Executive Officer
Atlantic Richfield Company



A brief overview of where we are in the energy situation and how we got there is in order because we are in a situation which can only be described as truly grim. We do have an energy problem. We're the only country in the world that does not seem to recognize it, but I can assure you that it is real.

Henry Ford started it. The introduction of the motor car was the beginning of what we know as modern energy use. In 1920 it was a question of which would give out first — dirt roads or gasoline. Gasoline hit 25¢ a gallon — probably its all-time high price on a constant dollar basis. Fortunately, two discoveries of oil in Los Angeles saved Henry Ford and the automobile industry — Kettleman Hills and Midway provided oil to support the eastern seaboard. Oklahoma City came along in the mid-1920s and took care of the growing industry. But the real windfall was the discovery of the east Texas field in 1931-32. This field was so large that it completely dwarfed all known discoveries in the United States or anywhere in the world at that time. It carried the United States and its allies comfortably through World War II.

The east Texas field and subsequent discoveries created the feeling — the myth — that we're living in a world afloat with oil. This feeling of great relaxation was enhanced by the huge discoveries made in the Middle East. There are now some eight to ten oil fields in that part of the world which have come quietly to the forefront and now dominate oil production

The first test of oil production after World War II was in 1957 with the closing of the Suez, but Texas oil production — the mythical power — rose to meet the needs, and we passed that crisis with barely a bobble. In 1967 we had a repeat threat and this time the Texas fields had a little more difficulty meeting the extreme demands on them. Fortunately, the crisis was rather brief and was quickly passed.

At this point, I would like to drive one point home. There are two ways by which you gauge the availability of oil. One is by reserves, and the other is the rate you can extract it. There are absolute physical limits to how fast oil can be taken out of an oil well. The chief problem today is getting to be producibility, not reserves. This is the first time the world has faced that limitation.

Let me give you an example. In 1970 the state of Texas decided to remove all controls on oil production other than those that were absolutely necessary for short-term needs to protect oil and gas ratios. Now, according to popular and conventional wisdom at the time, Texas had a shut-in capacity to produce an additional two to three million barrels a day. But when this producing capacity was released, it turned out to be virtually non-existent. Within a year, Texas production had settled back to roughly where it had been before de-control — some ten million barrels a day.

For many years, OPEC countries had been dominated by the threat that the United States would, if necessary, release this vast quantity of oil in Texas to keep the OPEC prices under control. It worked, and until 1970 very little oil from the Middle East was sold at a price as high as $1 a barrel. Of course, once this sword was removed from over OPEC's head, OPEC became a viable and a very effective cartel. By early 1972, it had negotiated its first worldwide price increase to $2.50 a barrel, a huge step forward because it proved that these countries could move in concert.

When OPEC realized that the embargo it had imposed in 1973 was failing, its first move was to double the price of petroleum to $5.50 a barrel. That didn't seem to get the world's attention, so between Christmas and New Year's of 1973, it just decided to double the price again — to $11.00 a barrel — and see what would happen. Amazingly enough, that price stuck, and I think OPEC was more surprised than anyone else. What had happened was a quadrupling of world oil prices in a matter of six or seven months.

The reactions were interesting. The rest of the world's consumption of petroleum declined rather significantly in response to the price and the recognition that there were problems with each nation's balance of payments. Developing countries in the extreme and even Europe and Japan significantly reduced their consumption. The only country that did not was the United States, which significantly increased its consumption and its imports.

Now this was the scenario when we moved into 1978. I believe, and I am going to climb out on a limb here, that history will show that world oil production peaked in the last six months of 1978, and in all probability that peak will never be reached again. Figures released in the fall of 1979 by the International Energy Agency in Paris would support this contention.

The collapse of Iran really triggered the start of the decline of world oil production, which this year will probably be down one to two million barrels below the level of the last third or fourth quarter of 1978. This is being driven home very dramatically by something that is not generally known; the present price of world oil is nearly $40 a barrel. The official OPEC price of $22 to $24 ($18 in Saudi Arabia) has practically no relationship to the going price of oil on what has become an open-market economy. We have in the world today a totally free market, and no one knows where the market price will go.

There are indications that price is beginning to have an impact on consumption. Consumption in the United States has gone down for the first time in nearly 50 years. The decline is 6 to 7 percent, which corresponds to 1¼ to 1½ million barrels a day, and so it is significant.

A number of other factors are emerging. First, in the last ten years the production industry has moved to where nearly 3/4 of the world's oil production is in the hands of governments or government-owned oil companies. It is no longer controlled by private industries as it was 20 years ago but is highly nationalized. In the final analysis, you are dealing with governments.

Second, there is a growing tendency for government-to-government negotiations and deals. Two years ago our government intervened for the first time in a negotiation with Mexico for gas. In that case, it was counterproductive and only created hard feelings with Mexico. I would hope this is not the start of a future trend because government-to-government negotiations invariably bring in political considerations. Unless the free-market economy is separated from political decisions, there will be pressures in various parts of the world that will be extremely difficult to deal with.

Another recent happening, one which is very difficult for us to comprehend, is that for the first time the majority of earnings in this industry come from overseas. The rather startling third-quarter earnings of international companies drive this home. Excluding the independent operators, somewhere between 60 and 67 percent of the industry's earnings come from sales and production abroad. The industry is becoming a little like Volvo in Sweden and Sony in Japan. The hue and cry that is now coming out of Washington corresponds to the Japanese complaining that Sony is making too much money selling television sets to the Americans. These earnings from abroad are really a positive benefit to our balance of payments. (I am sorry to say our company is a totally domestic company so we're on the other side of the fence, but I can admire the pasture over there.)

We are moving into an era without any precedent. Production in the United States is declining at the rate of half a million barrels per day per year. The official response to this crisis is what I call a liquidation tax — the government calls it excess profits — but it is a unit liquidation tax on existing domestic reserves which will insure the revenues will go to the federal government rather than to the industry itself. We will still have in no way come to grips with the problem.

What are our energy options? Solar, of course, in the long range offers remarkable benefits, but it is working on a different time scale than we are. Nuclear and coal still are our only two large viable options.

We have an enormous problem. The biggest part of it is convincing the American public. Washington has conventional wisdom that says the industry has vast quantities of oil still hidden in the ground, that when Texas was turned loose that hidden capacity to produce did not show up so it must still be there. Actually, it was dissipated during a period in which we were importing oil at $1.00 to $1.50 a barrel and enjoying air-conditioning the sidewalks in front of Sears Roebuck stores. Until we can remove the myth that there is unproduced oil — hidden oil — our credibility is lost and the chance of getting our story across near impossible.

There is one thing that I would like to leave with you: that cross-over when demand would exceed supply, which everyone agreed would happen in the mid-1980s or 1990s — it happened last year. We are on a declining curve, and we have a lot of lessons to learn along with it. □

Energy Perspectives

Robert S. McNamara
President
World Bank

I want to start by making two general points that are not accepted by the American people today — and until they are I think the United States is going to be in trouble. Next, I want to make some general comments on the nature of the energy problem, and then shift to a discussion of something that I know a little bit about: the developing countries, and the effect of the problem on them. Finally, I want to draw a conclusion, and that conclusion is this: Although the energy problem does entail a very heavy cost to American society, it is not an insurmountable threat to the economies of either the developed or the developing countries.

The first of my two general points is that it is wrong to think that the current energy problem is a crisis. It is a problem that Americans are going to have to live with, and are going to have to learn to manage, but there aren't any identifiable devils or villains that have caused it. It's not the oil companies' fault, and it's not OPEC's fault. Nor is there any identifiable victory at the end of the line. As a matter of fact, there isn't any end of the line. Rather, it is something that Americans are going to have with them for the rest of their days, their children's days, and their grandchildren's days. They are just going to have to learn to manage energy as they manage many other aspects of their society.

My second general point is that we should thank God for the increase in the oil prices. Where would we be in 1985 or 1990 if we were still consuming $2-a-barrel oil? In fact, imagine where we would be today if we were consuming $2-a-barrel oil or, adjusted for inflation, $3.50 versus whatever it actually is, $22 to $40. We have failed to adjust adequately to this problem, but at least we have begun to adjust in ways that we would not have done had we still been consuming $2-a-barrel oil. In that sense, we are better off because of the price increase.

Actually, the problem isn't so much that the prices have increased; the problem is that the increases have come without anticipation, abruptly, and in lumpy amounts. There was, initially, the quadrupling or quintupling in 1973, and then between September of last year and June of 1979 there was an additional 60 percent increase. What hadn't been generally recognized is that the real price of oil declined rather substantially — perhaps by 10 percent in real terms — between December 1973 and the end of 1978, and then rose by 60 percent in real terms very suddenly. The U. S. wasn't prepared for that. So that's one problem: unanticipated, lumpy increases. And the second problem is that the increment goes to relatively few countries — the OPEC nations — and is diverted from most of the other economies of the world.

The prices, of course, are going to continue to rise, though no one knows by how much. I would guess that the average price is going to double between now and the end of the century, which would mean about a 3½ percent a year increase. We are going to have to anticipate that. We need to plan for it, and I think we can.

Now, let me make some general comments about the nature of the problem. The world is not running out of energy. We have lots of energy, but there is a problem with the cost. That's why I say we're lucky the price rose when it did. If we had waited ten years to have that price increase, we would be less able to mine, if you will, the very large resource of energy that still exists in the world.

In this situation of continuously rising prices, conservation is clearly going to be one of the principal required adjustments. It is going to be at least as important as the expansion of nuclear energy and the expansion of coal, both of which will take time to implement. Conservation is something the U. S. can deal with right now. The society hasn't really begun to conserve energy seriously. When one looks at what the Japanese and the western Europeans have done, one can see tremendous unexplored opportunities for conservation. Nevertheless, the practical realities are that during this next 20-year period the U. S. is going to be dependent on Middle Eastern oil, and that oil is an unreliable source of supply. Perhaps the most important problem the U. S. has today is to adjust to that dependency, and to anticipate interruptions in the Middle Eastern supply of oil.

It certainly can't be very easy being the U. S. Secretary of State under these circumstances. America is in a very awkward position and has given itself almost no bargaining power. As a society, it has been improvident in this matter. The problem affects much of its activities — its relationships between various elements of its own American community, its relationships with other nations, and virtually every aspect of its political, economic, and social life. And the nation as a whole hasn't begun to adjust to all this. Clearly, one response that it can make — and one particularly relevant to Caltech — is to speed the shift to new energy sources by expanding the research and development effort. Not nearly enough attention has been directed to that.

Now let me turn to something I do know more about, namely, the developing world. What is this developing world? Well, excluding the People's Republic of China and a few other centrally planned economies, there are roughly 100 developing countries that the World Bank deals with. They have a population of 2¼ billion people. One and a quarter billion of those 2¼ billion people live in what we call the poorest countries — India, Bangladesh, Upper Volta, and so on. Their average energy consumption per capita is 166 kilograms of coal equivalent per year. In the United States it is 12,000; in the Federal Republic of Germany, 6,000. The U. S. has a long way to go in conservation — not that it could get its 12,000 down to 6,000. The U. S. is, after all, a much bigger country, it's colder, and there are other reasons why it should consume more than the Federal Republic — but not 100 percent more.

But there are 1¼ billion people in the poorest developing countries consuming 166 kilograms equivalent of energy versus the U. S.'s 12,000. That is going to change. There is a tremendous energy requirement lying ahead if these people are to move upward in the most fundamental human terms. They need more calories, and they cannot get more calories without more energy. I think their per capita consumption of energy will probably quintuple by the end of the century. The United States must understand that and take account of it.

In the short run, the problem of these poorest developing countries isn't energy; their problem is money. Their energy bill has increased tenfold since 1972, from $5 billion to $50 billion a year. There are only two ways to deal with that. Reduce the consumption — and that is pretty difficult when, per capita, you are consuming only 166 kilograms of coal equivalent energy per year — or reduce the rate of economic growth, a terrible penalty for their people.

Another billion individuals live in Brazil, Korea, Mexico, and similar middle-income developing countries, and they consume 900 kilograms compared to the U. S.'s 12,000. They don't have a great deal of room for conservation either. The only way to deal with their problem is for the developed nations and OPEC to help them finance it. I submit that it is in the interest of the developed nations and OPEC to do so and that means, essentially, intermediation. We must take the increment of price, channel it through the world's financial system, and put it to work in the developed countries and in the developing countries as well. That is a primary requirement, and in the short run is much more important than finding new energy sources or anything else as far as the 2¼ billion people in the developing world are concerned.

The second requirement is to help them help themselves. There is a tremendous opportunity to expand the energy production in those countries. The best way to deal with oil prices is to reduce the pressure of supply and demand. It does not matter very much initially whether the additional barrel of oil or energy is produced in the U. S. or someplace else in the world. If the energy demand can be reduced, then the pressure on energy supply will be reduced.

Among those 100 developing countries, we in the World Bank estimate that 78 have the potential to produce oil. Only 23 are producing it, and those only in small quantities. But we think the 78 can expand their production by about 4 million barrels of oil and gas equivalent per day in the next ten years. It will cost some $12 billion per year to do it. And it is in the developed nations' interest to help raise that capital.

The World Bank is trying to assist in this. Within three years we expect to be associated with energy projects worth about $4 billion a year. This will help the developing countries to move towards that 4-million-barrel-a-day increment by the end of ten years.

So I come back to where I began: America is going to have to live with the energy problem for a very long time. The costs are huge. Energy is approximately 5 percent of this country's GNP today. If it doubles in real terms between now and the end of the century, in a sense that means a loss of 5 percent of GNP — 0.4 percent a year reduction in the U. S. growth rate. That is not something one would deliberately seek, but neither is it something one ought to feel overwhelmed by. The American people just need to address it in a determined manner, and so far they haven't. That, I think, is the real issue for the United States. □

Most of the people who talk about energy today unfortunately talk about it in terms of the distant future. They talk about what's going to happen in the year 2000. I would like to try to give you the perspective of the operating utility executive who has the responsibility for delivering the 110-volt current at your outlet today and tomorrow.

I think for most of our energy problems we look toward Washington as a focus. And unfortunately, a coordinated national energy policy has eluded at least three presidential administrations. Perhaps the reasons lie in the basic divisions in our society regarding energy. They include a disagreement about the kind of future people want, the morality of nuclear power, the legitimacy of continued economic growth, the degree of environmental preservation, and also a proper distribution of income. These issues involve more than just energy, but they have been injected on the energy circuit, and they provide what the electronic technician would call "noise" on the circuit.

Energy Perspectives

William R. Gould
President
Southern California Edison
Company

We have reached the point where the energy debate has become a testing ground, even a place of conflict, over the broader social choices. The process by which we make these choices is completely inadequate. We have to choose between adequate energy and environmental quality, health and safety and national security, and the system by which we do it practically doesn't exist. There has been too much political rhetoric on this subject, too much finger pointing, too much looking for the villain in the piece, and too much knee-jerk reaction. Not enough attention is paid to the factual analysis or the need to balance competing objectives.

Most of the government mechanisms in programs dealing with energy are ineffectual and very expensive. They compound our problems rather than solve them. As one writer has put it, our political circuits have simply become overloaded on the energy issue. The old process of informal compromise and implicit mutual accommodation no longer works. So in addition to needing a workable energy policy, I believe we need a workable decision-making process that will protect the market system and the other institutions that have allowed our country's standard of living to become the highest and the most envied in the world. We must, as a nation, agree on what our energy options are — what environmental trade-offs will be required, what risks we are willing to take. We must acknowledge that our country currently relies too heavily on foreign oil, where we have no control over cost or continuity of supply. A failure to change this fact could hold the horrible specter of another global war.

No single energy source holds the key to our energy future. If our nation is to meet the triple energy objectives of an adequate and dependable supply of energy, environmental protection, and economically feasible conservation, we will require a balanced energy mix that includes nuclear, coal, solar, synthetic fuels and other resources. In short, we are going to need every BTU and every kilowatt from whatever source we can find. Those who would say that any one single source is the answer — such as geothermal, solar, or whatever — are mistaken.

Clearly, the most likely technical alternatives to oil between now and the year 2000 are coal and nuclear. We have in this country a 300- to 400-year supply of coal if government restrictions and regulations are eased to allow this resource to be used with sufficient environmental safety regards. Coal could produce 40 to 50 percent of our electricty by the turn of the century, but unless I have missed a news item, there have been no significant federal coal leases issued in the last ten years.

Our country cannot achieve any energy independence from oil cartels without a substantial reliance on nuclear power. At the present time nuclear power is not generally regarded by the man on the street as being on the side of the angels. Certainly there is increased uncertainty over the future of nuclear power following the Three Mile Island incident. This accident was a serious matter but it must be remembered that no one was injured and radiation releases were well within safe limits. Despite what you may have been led to believe, the safety systems worked. In fact, the margins of safety were greater than what had been anticipated by the designers of the plant.

This is not to excuse what happened at Three Mile Island. Our industry has taken the incident very seriously. We have analyzed what happened, and we have learned a great deal about that particular kind of nuclear plant. We have taken important steps to assure greater responsibility for nuclear safety. The electric business, in concert, has formed the Institute of Nuclear Plant Operations. It has the task of establishing nuclear plant operating standards and setting criteria for operator training. It will conduct on-site audits of the operations — policing if you will — and it will monitor the industry's safety-related goals. This is an attempt on the part of the industry to go beyond what the regulatory agencies did, that is, to properly and intelligently police its own operations. This Institute will have an $11 million budget and a full-time staff of 200 people. It will also have a review board composed of prominent educators, scientists, and engineers from outside of the business.

A Nuclear Safety Analysis Center has also been established. It is currently carrying out a detailed technical analysis of what happened at Three Mile Island. Recordings were taken at three-second intervals at most of the critical system points, so we have a great mass of hard data that is now being evaluated by some of the most experienced technical specialists in the nation. The lessons we learn will be recycled in the operation and design of existing and future nuclear plants, and they will be thoroughly communicated with the public.

One of the things we found was missing in Three Mile Island was an adequate emergency response system. So we have, within the industry, established an emergency response plan that will serve as a pre-planned, organized approach for improving the overall coordination and communication in the event of another emergency situation. It will also set up procedures for operations and for shutdowns, and will establish a national inventory of experts and equipment that can be rushed on-site promptly when needed. Incidentally, we have in southern California a nuclear power plant that has operated for 12 years, producing enough kilowatt-hours to save the rate payers up to $7 million in each of these years. Over its 12-year operating life, San Onofre Nuclear Generating Plant has experienced 12 near full-load shutdowns of the turbine generator, and in no case has the unit experienced operating difficulties or problems.

As a nation, we cannot give up the nuclear option. Further, I don't think that we can give up the option to recycle plutonium, nor to develop the breeder reactor. To me the best place in the world for plutonium is behind 12 inches of high-tensile steel and some 18 feet of concrete, making kilowatts rather than being a threat in the minds of many throughout the world. If we don't recycle plutonium and if we don't build the breeder, the rest of the world is going to do it, and it will become a producer of electricity in the world anyway.

The most dangerous course of action this nation could take as a result of Three Mile Island would be to abandon the nuclear option as a source of electric power. If that were allowed to happen, the consequence for the country's economic and general well-being would be crippling. Our productivity would go down, and our ability to compete in the world market would decline to where, in my perspective, we would be a third-rate nation. In 1978, 7 percent of all capital spending in the United States was for nuclear plants. Eighty-three such plants are currently under construction. Seventy-two are in service at the moment providing about 13 percent of the nation's total electricity. Best estimates for the year 2000 call for nuclear power to provide 35 to 40 percent of our nation's electricity.

Conservation too will play an important role in our energy future. Our company is committed to it. We expect to spend $20 million in our conservation program in 1979. But the fact is, conservation over the long term can only slow the growth in the demand for electricity — it will not stop it. Here in California, for instance, prior to the oil embargo of 1973, we had forecast the need for over 11,000 megawatts of new generating capacity to serve what we then expected to be the 65,000 new customers we would add each year over the next ten years. The only number that has not changed in this estimate is the new customers number. We expect as many as 90,000 new customers this current year. We must have additional capacity to serve them. Since the oil embargo, we have reduced our forecast of 11,000 megawatts by some 6,000 megawatts because of current and anticipated customer response to the call for conservation. We have achieved that conservation in part because the price of the product has gone up dramatically, tied as it is inseparably to the soaring cost of foreign oil. But nevertheless, this is a significant company/customer effort. The fact remains, however, that we still need 5,000 megawatts of new capacity for the coming decade. That's about 40 percent of our existing capacity, and about half of this new capacity is expected to be nuclear. This will come from San Onofre units 2 and 3, which are currently under construction, and a share that we have in a nuclear power plant under construction near Phoenix, Arizona.

Other large increments of our future capacity are moving along as scheduled. These include a major coal-fired station at one of five proposed sites in southern California where for the first time in this state we're going to attempt to burn coal as coal. We plan to build a combustion-turbine "peaker park" near Lucerne Valley. A peaker park is a series of combustion turbines, similar to jet engines, that can be put into operation on short notice. Unfortunately, they require a sophisticated fuel. They can burn coal-derived fuels, oil and liquid, but they can't burn coal. So we have to have a synthetic fuel program under way to provide fuel for them.

We are working very hard in research on virtually every known feasible alternate source for generating electricity. Our R & D program for 1979 totals $32 million, one of the highest outlays of any investor-owned utility in the United States. We're already participating in a number of alternate energy projects — solar, wind, thermal, fuel cells, and magnetohydrodynamics. In addition, we are actively pursuing the development of synthetic fuels including gasified and liquefied coal and shale oil. But we are dealing with new and untested technologies. Realistically, these alternative energy resources can be counted on to contribute only a small percentage to our generating resources by the turn of the century.

The cost of these sources will be high, almost prohibitive. For instance, our 10-megawatt solar plant that is now being built near Barstow is expected to be completed in 1981. This is a pilot plant, and the cost per kilowatt-hour of electricity will be in the neighborhood of 80¢. Electricity from our 3-megawatt wind turbine that is being built in the desert will probably cost around 12¢ per kilowatt-hour. And from our first geothermal plants and coal gasification plants, electricity will be in the range of 14 to 15¢ per kilowatt-hour. Compare these figures with nuclear power, which currently costs 1.5¢ per kilowatt-hour, coal about 2.3¢ per kilowatt-hour, and oil about 4¢ per kilowatt-hour. Over the long term as technology is developed, I expect the solar and wind costs to go down, particularly when photovoltaics start to come on the scene. But until then, our energy options, at least the economic ones, are limited because customers cannot afford to pay 3 to 20 times more for their electricity than what they would with existing means of production.

Coal and nuclear power are here now as alternatives to imported oil. They are economic, we have the technology. Other so-called alternate energy sources are not here and now, nor will they be to any significant degree for at least another decade or two. The answers to our near-term energy futures are clear. What we need is the necessary decision-making process that balances the conflicting interests, and toward this end, I hope we will all work together. □

Dean A. McGee
Chairman and Chief
Executive Officer
Kerr-McGee Corporation

We all know that coal is one of our most viable alternative energy sources, and I would like to try to put the coal business into perspective with regard to our overall energy situation. Coal satisfies all of the criteria necessary for a near-term major addition to our energy supply. It is plentiful, the technology to use it is available now, there is an existing infrastructure on which to build, and because of its chemistry, coal can be converted into a wide range of fuel products. For these reasons, coal is the cornerstone of the government's program for offsetting the growing shortfall in the domestic supply of hydrocarbons.

Coal comprises some 70 to 80 percent of this country's energy reserves, but at present it only supplies about 20 percent of our energy requirements. Domestic production of coal has increased only slightly in the six years since the oil embargo. And in these six years, many new regulatory restraints have been placed on the mining, transportation, and burning of coal that have substantially increased the cost of its production and use. The government's programs for developing the technology for the conversion of coal and for first-generation demonstration plants have been few. Thus for a decade or two, most of the coal used will have to be burned as solid fuel.

Coal, of course, was the fuel of the Industrial Revolution. It was coal that powered the transition from an agricultural and wood-burning economy to an industrial one. But the use of coal did not grow with the economy. The United States is estimated to have about 30 percent of the world's recoverable coal reserves. Of the estimated 1.7 trillion tons of coal reserves in this country about 214 billion are recoverable at present cost and with present technology. Coal is widespread geographically, with mineable deposits in 37 of our states.

Coal production grew rapidly in the early years of this century. Of the total energy produced in 1923, coal provided 73 percent, and oil and gas 23 percent. This level of production was not surpassed until 1947 when coal comprised 51 percent of the total energy produced, and oil and gas 45 percent. During this period of 24 years, total energy demand in this country grew steadily, but petroleum fuel captured most of the growth.

Following World War II, a number of large-diameter gas transmission pipelines were constructed. In 1954 the United States Supreme Court decided that the Natural Gas Act of 1933 gave the Federal Power Commission authority to control the wellhead price of natural gas. These two occurrences made an abundance of below-replacement-cost, clean, natural gas available in most parts of this country, and the production and use of coal declined steadily. In the early 1960s the production of coal declined to less than 400 million tons. By 1976, coal's share of the energy market in this country had dropped to 20 percent, and oil and gas had risen to 76 percent. Production of coal has continued to increase slowly and currently is around 700 million tons annually.

For the past quarter of a century, coal has been the victim of federal energy legislation and regulation. Energy price regulation, environmental restrictions, safety and health requirements, use controls, and often contradictory and overlapping government policies have effectively limited the production and use of coal. As an example, my company has been trying since 1975 to put a large surface coal mine into production in eastern Wyoming. A brief review of what has happened in the intervening 4½ years will illustrate the type of problems the coal industry must now overcome to assume a larger share of this country's energy demand.

A lease on the coal property was obtained from the government in 1966. The lease has a clause requiring that approximately 10 million tons must be produced by June 1, 1986. The initial application for the permit to mine was made in February of 1975. Preparation of an environmental impact statement was begun in 1976. In 1977 a new revised mining plan was required. In April of 1978 the government advised that the plan would have to be changed to conform fully to the requirements of the Office of Surface Mining. In 1977 an application for a mining permit was also made to the Wyoming Department of Environmental Quality. The original application to the state of Wyoming was one two-inch-thick report. The recent application was six three-inch volumes, and in addition one state agency required 50 copies. We do not yet have a permit to mine, but unless we mine 10 million tons of coal by 1986, we could lose a very valuable property. Here are some of the more interesting questions that some of the regulatory agencies ask. How will the cattle trails be reestablished in the final reclaimed area? What color will the service buildings be painted? Where will the blasting materials be stored? And many more going on in the same vein.

With the sharp, continuing increase of world oil prices since 1974 and the plan to reserve gas for premium uses, the cost disadvantage under which coal has competed for decades is beginning to be reversed. Coal at the mine mouth now has a competitive advantage in a number of areas. However, the cost of transportation, storage, environmental and health and safety requirements, increased severance taxes, and royalties has significantly offset any mine-mouth cost advantage. Partly to stay competitive, there has been a shift from underground to lower cost surface mining and from eastern to western coal. Sixty-three percent of the coal mined in 1978 was from surface mines. In 1970 the production east of the Mississippi River accounted for 93 percent of total coal production. It is estimated that by 1990 this percentage will have shrunk to 59 percent. The occurrence of very thick coal seams (up to 100 feet) with thin overburden in eastern Wyoming and Montana is largely responsible for this shift.

As the domestically produced supply of oil and gas continues to decline — and it will — the future for coal seems to lie in two areas: for electric power generation and as a raw material for the production of synthetic fuels. Unless the government uses the authority it now has to mandate that the existing oil- and gas-fired utilities shift to coal, there will not be a dramatic increase in the production of coal. The future for a greatly expanded use lies in this country's success in transferring its energy base for liquid and gaseous hydrocarbons from oil and gas to coal. The technological challenge confronting the adaptation of coal utilization to our existing infrastructure is related to three characteristics of coal: It is dirty, it is solid, and coal resources are not always located at points of major use.

Because this country is responding to an energy crisis, coal-utilization concepts under most vigorous development today are those that can be commercially implemented at the earliest date. These are, for the most part, an engineering upgrading of first generation coal-utilization technology, namely direct coal burning, coal liquefaction, and coal gasification. But these processes are a stopgap measure.

The coal industry of the future will probably be structured around an entirely different concept, similar in many respects to the way the petroleum industry is structured today. The petroleum industry developed a technology for the separation of crude oil into components that best fit a wide spectrum of needs. The ultimate coal industry can be visualized as having the same general characteristics, with coal being separated into many components to fill an equally wide spectrum of energy needs. To achieve this, the coal industry is in need of a technological breakthrough, a concept that would do for coal what distillation has done for petroleum.

The needed coal-separation process should remove ash and other impurities and should separate coal into a hydrocarbon fraction for liquid fuel uses, another hydrocarbon fraction for gaseous fuel uses, and a high-carbon, high-BTU fraction suitable for electric power generation. At the present time, the technology for breaking coal into these general end uses is not available. However, many separate coal-conversion concepts for producing clean-burning fuel, synthetic crude oil, and synthetic natural gas are beginning to merge into a concerted effort for the optimum utilization of coal. Perhaps the needed breakthrough is just over the horizon. Coal, the United States' most readily available, largest energy resource, has not yet begun to fulfill its potential for making a large contribution to our energy needs.

As for the world situation in coal, as you probably know, Australia and South Africa are large producers. Of course, the European countries — Germany, France, Britain — have been producing coal for centuries. But we recently have had visits from both the French and the British asking about the possibility of acquiring equity interests in coal deposits in this country. They anticipate that Europe alone will need some additional 85 million tons of imported coal by 1985. So the world is going to look to the United States in the next decade or two for a part of its coal needs. □

Knowing I was scheduled to be the last speaker, coming after several distinguished experts, I decided that flexibility would have to dominate my preparation. So I came up with a list of some 50 points I thought ought to be mentioned in a symposium on energy. Then I sat and crossed items off as they were covered by others. Soon I began to worry that nothing would be left for me to bring up — and that almost happened. In fact, the other presenters covered everything on my roll except one issue. That one, amazingly, was not even so much as mentioned. It is merely the energy program of the administration in Washington! I say amazingly, because, after all, President Carter, you may remember, came down from Camp David and delivered a major TV address billed as the most important of his career. He said he wanted Congress to approve, and the nation to back him in, a massive project to create a syn-

Energy Perspectives

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thetic fuel industry in the United States to cost over $100 billion. To carry this out, he proposed two new government agencies: one, the Energy Mobilization Board with duties to expedite things, to beat the other bureaucracies over the head so they'll quit standing in the way; and the other, the Energy Security Corporation, a new operation with that $100 billion to spend to get synthetic fuel rolling.

Now, as we all know, in the United States there are two ways to get something done. Either the government does it, or free enterprise does it. Perhaps the nation is divided into three halves on this subject. One half says, "The way you get things to happen right is keep the government out and let free enterprise, which made this nation great, do the job." Another says, "What? Look to the selfish, profit-seeking private sector? They certainly do not have the nation's interest at heart! Government action is the only way to go." Approximately half the people in the nation believe the private enterprise system, and big business in particular, is no damn good. Another half says the government is a wasteful, inefficient, incompetent bureaucracy and can't do anything right. A third half holds both these views at once.

Now, both of these extreme views are wrong, particularly as applied to energy. You can rightly be accused of being out of date if you imagine that a total free-enterprise, private-sector solution to the energy problem is in the cards for the United States. The situation is much too political for that and isn't going to change. The government is in energy in a big way, and the government is going to stay in it. But the government really is a big, wasteful, inefficient, largely incompetent bureaucracy, and you can't get anything done without the expertise — management, technological, economic — of the private sector. So the trick, the name of the game, the real solution to the problem — as is true of a number of other problems involving science and technology in our nation — is to have the right combination, the right roles and missions, the right teaming up of government and private industry. This is what we have to work toward.

Those who think in terms of the private sector's handling energy matters alone look upon the President's program as taking hundreds of billions of dollars out of the private sector and handing them to a government agency to do a job it is not competent to do. The government will hire a huge group of amateurs to direct synthetic fuel approaches — what and where and on what time schedule, and with what kinds of technologies, controls, and allocations. Of course, there will be some outstanding people at the top — not outstanding in the sense of having energy experience, because that is ruled out by the peculiar U.S. interpretation of conflict of interest — and a good many of the government's staff will be trying desperately hard to do what is right for the nation. But by and large, it just isn't in the cards to solve the energy problem with syn-fuels if that whole program is going to be directed by a new government agency, with industry simply trying to respond to the highly politically dominated decisions of the government. The environmentalists are also concerned about this approach because they see the proposed new Energy Mobilization Board as simply a way of getting around the reason why all the other regulatory bureaucracies were put into existence in the first place.

But there's more to it than this. There are a lot of alternatives to the energy problem in the United States and they all have their zealous advocates and their detractors. The conservationists, for example, say that for less capital investment and technological effort than will go into syn-fuel we could pay for changeovers in industry, our homes, and our cars, so as to use a lot less energy. A barrel of oil saved is a barrel produced. And if you can save it with less cost, with less change of lifestyle, with the least concern about the environment, then that's the thing to do.

Another voice comes from the nuclear advocates who argue that we have allowed that whole area to become emotional and political, and that, while past attention to safety, waste disposal, and so forth may not have been totally adequate, we certainly can rise to the additional requirements. And there are those who will tell us that the reserves of oil in the existing oil wells can be doubled if we apply new technology to bring the oil up when it becomes reluctant. Of course, that will cost money, but not as much as creating a whole new synthetic fuel industry under a massive government program. There are solar advocates who favor solar panels on the roof to heat water, solar cells to go from sunlight directly to electricity in homes, and solar conversion on an industrial basis through techniques such as biomass or through Caltech's Harry Gray's catalysts to break up ordinary seawater into fuels of hydrogen and hydrogen peroxide.

Of course, there are also detractors of these alternatives. (Most of the claimed negatives you are familiar with, but let me describe one with which you might not be. Imagine that millions of homes come to have solar panels on their roofs, and they're generating some or perhaps all of the electricity needed. Now, these panels must be kept clean. Even with the greatest of ingenuity in the design of brushes and other aids, millions of homeowners will have to use roof ladders once a month. Considering the statistics, we can expect that the number of deaths and broken bones will exceed automobile fatalities and injuries.)

All energy alternatives have shortcomings, all need effort for solid development, all need government/private cooperation. To fully satisfy our criteria, they all need environmental and safety controls. In total, they're all tough to bring off. So we need to work on a lot of alternatives in parallel, not knowing which will really work out. Synthetic fuel is just one option.

Let's consider more carefully a completely free-enterprise solution to syn-fuel. Imagine that we are the Board of Directors of a large corporation that knows how to create synthetic fuels from coal, and we decide to go do it. We know that we have a ten-year period ahead of us before we will get any return on our investment. The investment will be around $10 billion because we have to be talking about doing this on a substantial scale. We will need to meet severe environmental requirements set by the government. These we can only guess at, and they will get more severe all the time, even as we engage in the planning and the building of the facilities. We will also face the possibility of being sued by the government based on anti-trust laws, because to be successful we will probably have to put together a syndicate of large corporations. Private suits on numerous grounds will also be filed. Finally, after several years, when we get the whole thing operating and we are producing substantial output to meet the requirements of society at a price we believe is sensible, and that the market is willing to pay, the government will step in and clamp on a new and lower ceiling price that we are permitted to charge. When we complain that the new price is so low we will not realize anywhere near a fair return on investment — we wouldn't have gone into it in the first place had we known they were going to apply that price control on it — the easy thing for the government is to say, "We know you're lying. You're obviously making money hand over fist." If you think you can make the public believe we really need the return, then you're too naive to be on the Board.

Anticipating all this, the Board of Directors will veto the investment at the outset.

So, we have rejected a totally government-run syn-fuel program as too incompetent and political, and a private program as unreal. But a sound and practical way to set up this project exists. Its emphasis is on assigning the right roles and missions to government and the private sector. The scenario goes like this: The government announces that, for the government's own use, it wants to purchase from the private sector synthetic fuel to be made from coal through a competition. The government states the quality and nature of the fuel it wishes to buy and the delivery schedule. It offers a ten-year contract with a price adjustment factor for inflation during that period. The government uses a formula for deciding on the competition winners with credit given both for low price and early start on deliveries. The government sets standards as to safety and pollution that it agrees not to tighten without upward price adjustment. The government plans to obtain these requirements — say of the order of a half to a million barrels a day equivalent — from at least two sources. The government provides immunity from antitrust if companies wish to create a joint venture to bid on the proposal. The government provides a proper cancellation fee if it wishes to cancel part way through the ten-year priod.

If the government were to issue this request for proposals, a number of firms of high competence and substantial financial backing would bid. The submissions would be sensible from the standpoint of the bidders because they otherwise would not submit them. Doubtless the prices quoted in the proposals would be higher than existing petroleum prices but, from what we already know of the technology and economics, not so high as to vitiate the program. The requirements for access to suitable land and water resources for the coal would be included in the proposal and ultimate contracts. State or federal land would have to be made available at particular locations at stated price ranges as part of any deals made. Obviously, the legislation creating the program described could include provisions for the designated government contracting agency to have some of the same powers to accelerate law suits and regulatory approvals that President Carter has envisaged for his otherwise quite different Energy Mobilization Board.

If this program were created, it would fully cover the requirement to get started in a meaningful way on synthetic fuel. It would set up the option to broaden the program later or keep it as a lower level program. The worst that could happen, from the standpoint of the government, is that if foreign oil did not rise enough in price during the contract period — and we would welcome that unlikely occurrence — the government would overpay somewhat for the fuel it would have purchased for its own needs.

As to appropriate roles for both the private sector and the government, we notice that in this proposal the government is not at all involved in the technology, an area where it has the least contribution to make. The government creates a guaranteed minimum market for the output of the private sector. The government sets safety and environmental standards, which it alone can and must do. The free-enterprise industry takes a calculated investment risk, choosing the technology it favors. If it wins the competition, it will direct its program. The government will not. □

Caltech social scientists recently turned their attention to a traditional problem of all universities — how to decide which students deserve scholarships. Forty merit scholarships to allocate among 150 Caltech undergraduate applicants — this is the annual chore faced by the faculty committee on financial aid to undergraduate students. Usually the task takes several days and is characterized by much wrangling and dissension before the "top 40" candidates are agreed on. Last spring the eight-member committee arrived at agreement in three and a half hours. They did it by auction.

Forrest D. Nelson, assistant professor of economics and chairman of the faculty committee on financial aid, designed this new procedure for the committee by adapting work done by Caltech social scientists John Ferejohn, Robert Forsythe, and Roger Noll on auction-like procedures for group decision making. The problem they have been examining is the situation in which a group must select simultaneously several alternatives from among a large set of possibilities.

Although most organizational decision problems have not been traditionally viewed as economic "markets," market mechanisms can be used to provide some elegant solutions to non-economic problems. The principles that are known to govern the behavior of markets are being applied to the design of new methods for processing information and making choices in the presence of conflicting opinions. The faculty financial aid committee's task is one such case.

An "auction" of scholarship candidates may be unique, but most people have some familiarity with more usual types of auctions — art works, stamps, coins, estate sales, for example, though they may not realize that there are different kinds of auctions. In the Dutch or "descending bid" auction the auctioneer starts with a high price and lowers it in increments until someone accepts the price. The more familiar English auction uses an "ascending bid" procedure. These are both oral auctions. There are also sealed-bid auctions, in which none of the bidders knows the bids of competitors.

Whatever the procedure, an auction is a mechanism for making decisions about the allocation of resources on the basis of bids submitted by individual participants in the process. Economists and other social scientists are interested in auctions because allocation of resources is what economic and political processes are all about, and auctions seem to be an efficient, widely applicable mechanism which exhibits consistent "law-like" behavior. The basic research question is how the design of the auction — the "rules of the game" — affects the outcome of the process.

Probably the biggest auctioneer in this country is not Sotheby Parke Bernet, but the federal government. Among the government's sales activities is the Treasury Department's quarterly customs auction, in which goods confiscated for failure to pay import taxes are sold to the public. These goods, mostly liquor and wine, are not sold individually but are broken up into packages, or bundles, of approximately 20 bottles worth between $100 and $200. Since the bottles in each lot often have no relation to each other, you can find a bottle of Chateau Latour '59 packaged with a bottle of rotgut. The customs auction provides a simple, easy to research example; goods are prohibited from being resold by buyers, and retail prices can be easily checked to determine the actual market value of the bundles. The sale is conducted as an oral auction with no set minimum bid. Graduate student Thomas Palfrey is studying the basic theory of this auction, addressing the general problem of why sellers want to bundle their goods this way rather than sell them individually or in homogeneous bundles (for example, a case of one particular wine). Do they make more money with heterogeneous bundles? Obviously, they think they do, but if so, why?

Palfrey's preliminary results indicate that the Customs Office is indeed acting in the taxpayer's best interests — in an auction with no set minimum the seller *does* earn more by bundling goods. The buyer in this case is at a greater advantage if goods are sold separately (perhaps because a person is more likely to have more information on the true value of a single item than of many unrelated goods in a package). However, if the auction requires a minimum bid, the opposite is generally true: The seller prefers to sell separately, and the buyers are better off with bundles, although there can be individual cases when the buyer also prefers separate items.

Other goods, besides wine, can be auctioned in bundles. Motion pictures have often been leased to theaters in this way. Palfrey was originally motivated to study bundling by his interest in government auctions for oil leases. The leases are sold by separate, simultaneous auctions for large numbers of one-square-mile tracts. The auctions are subject to a minimum bid requirement, and, as Palfrey's work predicts, the oil companies would prefer to bid on the leases in bundles.

Before bidding on the tracts — a process in which they compete — the oil companies cooperate in collecting information, and afterward also work collectively in exploiting the oil fields. The competitive market (the auction) is sandwiched between stages of nonmarket cooperation, all for the purpose of producing products that are also sold in competitive markets. Professor of Economics Roger Noll and graduate student Mark Isaac are particularly interested in the first stage — how the oil companies gather information about the tracts' potential for oil before they bid. There are rules and regulations about this: Some kinds of information may be kept by the company that produces it, while other kinds must be made available to others on a cost-sharing basis. And the government provides a lot of free information — such as that from the proposed Stereosat satellite, which will provide topographic mappings that may be useful in indicating where to explore for oil.

Isaac is exploring the issue of whether more information is necessarily good, and whether existing rules provide incentives to acquire the most efficient amount and kinds of data. He has shown that in some cases, free information will actually provide the wrong kind of incentives to the oil companies, promoting excessive competition in information gathering when cooperative behavior is more efficient. An oil company will be concerned about another firm using information to gain an advantage, and hence may overinvest in acquiring still more information. This will give firms less to spend on lease bids, exploratory wells, and reserve exploration, to the detriment of themselves, the government, and ultimately the consumer and taxpayer.

A better system would require greater cooperation in information gathering. Ferejohn, Forsythe, Noll, and Palfrey have recently applied their basic research on auctions for group decisions to the problem of designing a system for oil companies to use to decide collectively the amount and kind of exploratory data that would be most efficient and to allocate shares of the cost of acquiring the information. Since the whole system interacts to determine the motivation for oil exploration, its efficiency is vital to achieving the most efficient rate of discovery of energy resources.

A sticky feature of the problem is to construct a method that takes advantage of the collaboration possibilities without undermining the competitive structure of the industry by fostering collusion in other business activities. The advantage of the group auction approach is that it appears to the participants to operate like a competitive market but leads to a cooperative outcome.

One way the Caltech social scientists are going about designing these new auction methods is with experiments — studying how real people react in choosing among various monetarily motivated alternatives in a controlled situation. Economics and political science have historically not been considered experimental sciences. However, both economics and politics involve the study of choice, and back in the early 1970s it occurred to some faculty members at Caltech, where studies of economics and politics are closely intertwined, that it would be possible to create a situation involving choice behavior, to study it "in small" in the laboratory, and to use the results to test and to refine mathematical models of choice behavior.

Caltech Professor of Economics Charles Plott and alumnus Vernon Smith, BS '49, former Sherman Fairchild Distinguished Scholar at Caltech, and professor of economics at the University of Arizona, were pioneers in developing laboratory experiments in economics. The validity of this research method is now being cautiously accepted elsewhere. Four years ago only Caltech was involved in experimental economics; now a number of other leading research institutions are pursuing it, and Caltech graduate students are widely sought by other universities to introduce experimental methods into their instruction and research programs. Data from experiments are now finding their way into the government and industry policymaking process. And significantly, the National Science Foundation is supporting this kind of experimental research, having financed part of the work of every experimental social scientist on the Caltech faculty.

To be studied in a laboratory setting, a problem must be simple and carefully defined. If a basic theoretical model is expected to apply to complex cases, it must at least work in the simple, special cases set up in the laboratory. And although nothing absolutely conclusive can be learned from these methods about ''real-life'' situations, experimentation can lead to ''very informed guesses.''

The social science researchers recruit participants for experiments from all over the Caltech community and beyond — students, staff, JPL, the business community, and others. Those involved find the experiments to be fun, informative, and profitable — sometimes *very* profitable. Since one of the prime tenets of creating a market situation, or adapting market principles to nonmarket situations, is the profit incentive, subjects participate for cash profit, which they keep. Analysis of the experiments is based on the assumption that people will not generally cheat themselves out of the opportunity to earn money in these experimental situations.

Experimental methods have proven very well suited to investigating the properties of auctions. Plott, Gary Miller (a former Caltech faculty member), and undergraduate James Angel used experiments to study the processes used in the auction of Treasury bills, short-term notes sold to banks and other private lenders. Treasury bills are sold to the highest bidders under discriminative pricing; that is, you pay what you bid. Another way of auction pricing when numerous identical goods are offered for sale simultaneously under sealed-bid auction is the competitive or one-price auction, in which all successful bidders pay the price of the lowest accepted bid. Economists have not been able to determine the conditions that would make one type of pricing more advantageous than the other, or which process generates the most revenue to the seller. To find out, Plott, Miller, and Angel auctioned off securities within tightly controlled and monitored economic conditions. Each bidder was given a fixed redemption value schedule for securities that the experimenters would pay if he or she were a successful bidder. These values differed among subjects, and for a given subject the average value fell with volume such that, as the price of the bills fell, the number of bidders willing to buy them would rise. Experimental auction series were run using both types of pricing and different conditions of supply and demand. The experimenters were able to isolate some very distinct properties of the various auction organizations.

Each subject could make a sealed bid for one or more securities in each auction. The limited supply of securities would be awarded to the highest bidders, but the price paid depended on the type of auction. In the discriminative auction, each successful bidder paid the price he bid for the bill, so the individual who made a winning bid below his redemption value earned a profit equal to the difference between the redemption value and the bid. For example, if a security could be obtained by a successful bid of $6.00 by a person who could redeem it for $8.00, the successful bidder would make a profit of $2.00. Individuals submitting unsuccessful bids earned nothing. In such an auction the incentive to bid low to make a higher profit must be balanced against the incentive not to lose out altogether.

After each auction the highest and lowest successful bids were announced. In a series of auctions under stable economic conditions, the high bidders reduce their offers while those bidding too low increase theirs, and over time the bids converge neatly to an equilibrium price — the price that makes supply equal demand (that is, the price at which the number of units for sale equals the number that buyers are willing to purchase at that price).

Similar rules controlled the competitive auction with the exception that all those whose bids were accepted paid the price of the lowest accepted bid. What does that do to the bids? Most people tend to bid higher in such a situation; they want to be included in the accepted bids and assume they will probably not really have to pay as high a price as they bid. And what does it do to the earnings of the hypothetical seller, in this case the Treasury Department? Is the revenue generated higher or lower?

It depends, say Plott, Miller, and Angel. As a result of the very clear data obtained from the experiments, they can estimate almost exactly how much revenue would be generated by each method under different conditions of supply and demand. Which system is better overall depends on how dramatically the quantity demanded responds to a change in price. For example, the discriminative auction makes more money for the seller when the increase in quantity demanded, relative to a given price decrease, is low. When it is high, then the single-price auction becomes more advantageous for the seller.

So what should the Treasury Department do? Since the demand for Treasury bills is not very sensitive to changes in price, the government should probably use a one-price auction, say the Caltech researchers. This has long been suspected and suggested by economists, but before the Cal-

Auctions can get quite heated. This in not a riot but recent gold trading at the International Monetary Market, a division of the Chicago Mercantile Exchange.

Caltech students, also with real profit at stake, submit bids to the "auctioneer" in a pilot Social Science experiment to test theories on a barter economy.

tech experiments, there had been little empirical information to back up the claim. This illustrates an important use of experiments — to explore the performance of new institutional arrangements without risking vast amounts of wealth by immediately implementing them in some real situation.

The ability to generate hard data has led the Caltech economists to try applying auction mechanisms not only to already existing auction situations but to a broad spectrum of other market problems and even to situations involving the allocation of resources that are not ordinarily bought and sold. Auctions have been advanced as a more efficient alternative to government regulation. The use of experiments by Plott, Isaac, and Professor of Economics David Grether to explore new ways to allocate landing rights at high-density airports is one such example.

Eight years ago when the Federal Aviation Authority placed limitations on the number of planes that could land per hour at the country's four busiest airports, a committee of airline representatives was formed to decide among themselves who got to land when. Because the Civil Aeronautics Board decided the airline routes, it effectively controlled the committee.

Since deregulation of the airline industry in 1978, the CAB no longer controls the number of airlines operating at any particular airport. Airports now have more airlines competing for time slots in which to land their planes, and more airlines are represented on the deciding committee. Since Congress or the FAA might end up allocating slots if the airline committee cannot arrive at unanimous agreement, the larger airlines have been effectively forced to give up — grudgingly — some of their landing slots to the new arrivals. Although this process may seem "fair," it is economically inefficient, say Plott, Grether, and Isaac, because the decisions are not based on the underlying economics of the industry. In the long run the committee decision process will hamper the growth of more efficient firms and result in higher fares for passengers.

The Caltech economists ran experiments on the landing rights problem both ways — as a committee process and as an auction, where financially motivated individuals faced problems similar to those that the airlines would face when bidding for the time slots they desired. As a result of these studies, the Caltech team recommended to the CAB that slots be allocated by a sealed-bid, one-price auction with the additional provision of an "aftermarket," where airlines could trade the slots they had won. The economists also suggested that funds generated from the auction of the landing slots be used to expand airport capacity. As might be expected with any recommendation to solve such a complicated problem, aspects of the report are extremely controversial. Airlines, for example, aren't too happy about the prospect of buying landing rights that have historically been provided with only minimal charges. The application of experimental methods, however, demonstrated the plausibility of the technical analysis, and it appears that the recommendations of the Caltech team will become public policy.

One of the especially interesting potential applications of auction mechanisms is to allocate what economists and political scientists call public goods — that is, goods for which the costs and benefits are shared jointly by a group. Allocating shares of the cost is often difficult with public goods, since there is a strong incentive to take a "free ride" — let someone else pay for it but use it anyway. Once the good is produced, any number of people can use it at no extra cost; a case in point is the geological information that is generated about oil lease tracts. Numerous other situations of decision making by large groups involve public goods, for example, condominium residents with different incomes, ages, and tastes seeking to purchase communal playground equipment, or the executive committee of a multi-divisional corporation making decisions about a common R&D program that affects all divisions.

Generally, group decisions such as these are made by majority-rule voting, but for some purposes voting mechanisms are rather clumsy tools. They are not particularly efficient because they cannot readily account for intensities of preference and because they create incentives in some circumstances for participants to misreport true preferences.

Ferejohn, Forsythe, Palfrey, and Noll have been doing extensive experimental work in this area. The first case was the problem of purchasing programs for the public broadcasting network. A television program is a public good in that its production and distribution costs are essentially independent of the number of stations in the network that broadcast it. In the late 1960s, while at the President's Council of Economic Advisers, Noll proposed a market approach to program decisions. In 1974 the Public Broadcasting Service implemented the proposal, adopting an auction mechanism in which stations bid for the programs they want the network to broadcast. Shares of the costs of producing the programs are also assigned on the basis of bids. The system, known as the Station Program Cooperative, is an iterative bidding procedure in which, in each round, PBS sends messages on an interactive computer system to station managers about the programs that remain in the market. Each station is shown a "price" for each program that is calculated by dividing — according to a prearranged formula — the cost of a program among all the stations that voted for it in the previous round of bids. The station responds with an updated list of programs it wishes to purchase at the posted cost shares. A program is dropped when no station desires to purchase it at the last posted price, and is declared purchased when the sum of the accepted cost shares equals or exceeds the cost of the program. The rounds continue until so few changes occur in the station choices that the program prices faced by a station are virtually constant in two consecutive rounds.

The Station Programming Cooperative has been the basis for much of the experimental work on public goods. Refinements of this model and alternatives to it are employed to test new ways of discouraging "free ride" behavior and to perfect the auction's efficiency in different applications.

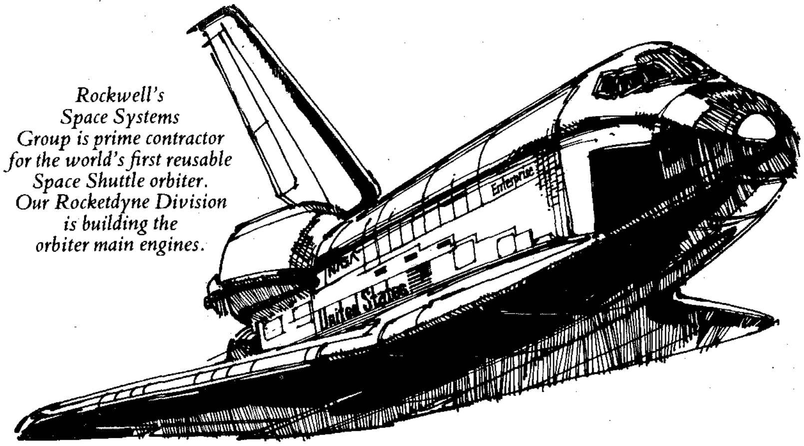
It was from this model that Nelson adapted his scholarship auction. The scholarships can be considered a public good in that the choice of the best qualified students benefits the entire committee (as well as the entire Institute), and each member of the committee must live with the decision.

Nelson's main problem in conceiving of the committee as a "market" or auction situation was the bidders' lack of any economic incentive. The stake of the committee members in the decision is purely non-economic, consisting of their personal preferences on intellectual grounds for one candidate over another. But Nelson designed a system that established an artificial cost by budgeting votes. What he ended up with was the adaptation of a simplified system "in the spirit of an auction mechanism," which worked well in this case.

First, each committee member listed his top 40 choices out of the total 150 candidates. When these were analyzed, those candidates on everyone's list were considered winners, and those without a single vote were thrown out of consideration. The rest made up the slate for the first round of balloting. The auction system was repeated in rounds, with the choices narrowed down in each round. Each committee member received a "budget" of votes. He could spend his votes on the remaining candidates by casting from zero to five votes for each one. After each ballot, any student receiving 20 or more votes was declared a winner and taken off the slate; since a committee member could cast no more than five votes, no scholarship candidate could be elected by a minority of the eight-person committee. Any candidate receiving less than a required minimum number of votes, which increased with each successive round, was also removed from further consideration.

In between rounds there was time for discussion of the candidates before balloting began again. Voting in rounds gave the faculty members a chance to reconsider candidates on the basis of new information and in relation to others of increasingly similar rank. On each subsequent ballot a voter's budget was reduced by the amount of his votes on winning candidates in the previous round, thus providing a "cost" incentive not to overspend. However, because a candidate could win with 20 votes, any surplus votes were redistributed to the committee members who had cast the greatest number of votes for that student.

It took four rounds and three and a half hours with only minor disagreements to choose 40 students for the scholarships. The faculty committee expressed satisfaction with the selection. Nelson admits that it is probably impossible to design a perfect auction-like mechanism for this case because of the absence of "real" economic incentives. And although the committee members thought the process fair, Nelson observes that the result was not necessarily perfectly "efficient"; that is, it may not have converged on exactly the 40 candidates that were the most qualified according to the combined committee opinions. However, majority-rule voting could not guarantee such an outcome either. For Caltech's financial aid committee the auction at least provided a more efficient means of reaching a complicated decision. □



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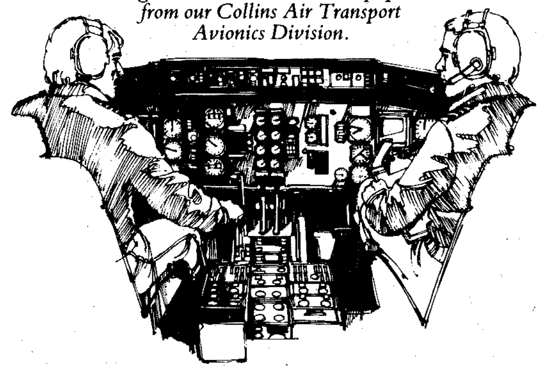

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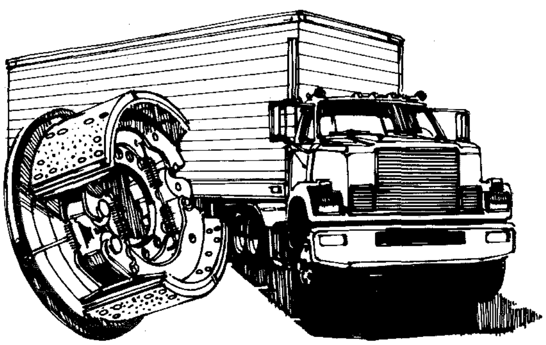

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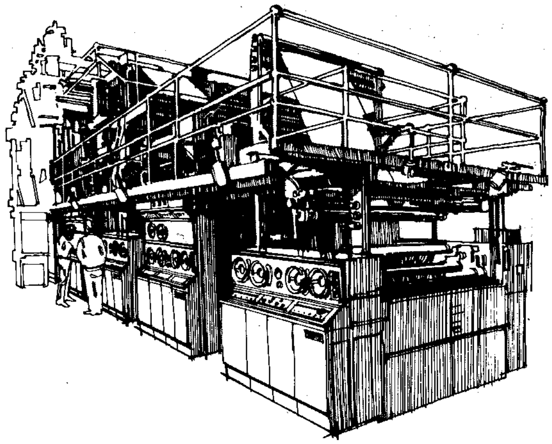

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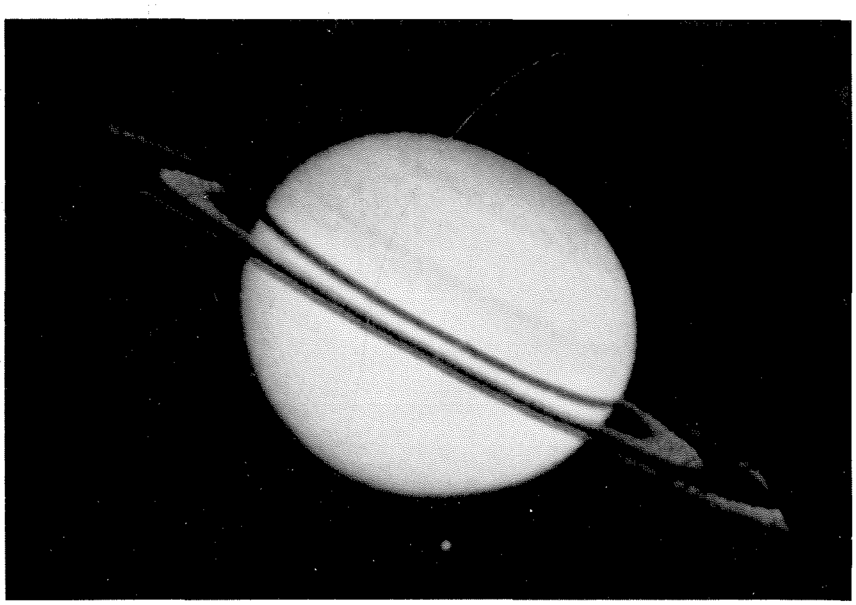
Saturn

Although the Voyager (1 and 2) pictures of Jupiter were a main feature of 1979, old Pioneer 11, launched nearly seven years ago, is still out there providing some very interesting information as well as some nice previews of coming attractions. Renamed Pioneer Saturn for its latest encounter, the spacecraft reached Saturn on September 1, 1979, passing through the ring plane outside the A-ring, and under the rings to within 21,400 kilometers of the planet's clouds. Its cameras took the closest pictures yet of Saturn, which, although they are not as close as and don't have the fine resolution of the recent Jupiter shots, still offer more detail than the best earth-based photographs. In addition to pictures, Pioneer's instruments sent back data that are revealing previously unknown facts about Saturn and helping to confirm theories about the solar system's formation.

For one thing, Saturn's helium is sinking into the planet's interior, says Professor of Planetary Science Andrew Ingersoll, principal investigator for Pioneer's infrared radiometer. Jupiter and Saturn and the sun have the same ratio, in bulk, of hydrogen to helium, the two most abundant elements in the universe. But whereas Jupiter appears to have that same percentage of helium (12 to 13 percent of the total number of molecules) in its outer layer where it can be measured, Saturn has approximately 6 percent.

This was discovered by superimposing the results of two experiments. The measurement by Ingersoll and his co-workers of the infrared radiation coming out of the atmosphere can be related to the temperature in the upper atmosphere, but this measurement is not very sensitive to composition. However, when JPL's Arvydas Kliore compared radio occultation data on the structure of the index of refraction for the same portion of Saturn's atmosphere with Ingersoll's temperature measurements, the composition shown in Kliore's results could be adjusted to match the temperature. About half the helium that should be in Saturn's outer layer isn't there.

John D. Anderson, also of JPL, was principal investigator for the celestial mechanics experiment. Using the Doppler shift signal in the microwave carrier that tracks Pioneer, he was able to measure Saturn's gravity field. Essentially, the spacecraft itself was acting as an instrument, allowing him to look at its motion and measure how the gravity field affected it. These data can be interpreted in terms of gravity sounding (a technique suggested by William Hubbard of the University of Arizona), which is the only experimental technique for "getting into" the interior of



Pioneer Saturn's imaging photopolarimeter took this picture of the planet and its rings 2,500,000 kilometers away, 58 hours before its closest approach. Here the rings are illuminated from below and look different from earth-based photographs where the illumination is from above the rings. The planet's banded structure can be seen particularly in the upper half above the distinct shadow cast by the rings. Saturn's moon Rhea is the bright spot below the planet.

large planets. Anderson's and Hubbard's data, together with Ingersoll's temperature measurements, show that Saturn's mass is concentrated at the center, which supports the conclusion that the heavier helium has sunk inward.

Ingersoll's infrared radiometer also discovered that Saturn, like Jupiter, has an internal heat source. Both planets have retained a significant amount of their primordial heat, generated 4½ billion years ago by the astronomical event that formed the solar system. Saturn, however, since it is less massive than Jupiter and farther from the sun, should have cooled off more than it has; the earth, although it is closer yet to the sun, has lost all but an insignificant part of its primordial heat because it is so much smaller. Discovery of this greater-than-expected internal heat source adds still more evidence to the argument that the helium is settling, since that process would generate heat.

Actually, the separation of helium had already been predicted. Theoretical calculations by David Stevenson, currently at UCLA, on the behavior of mixtures of hydrogen and helium at the high pressures characteristic of the interiors of giant planets indicated that the two elements should stay mixed on warmer planets, such as Jupiter, and separate on Saturn and other cooler planets. Pioneer's data bear this out.

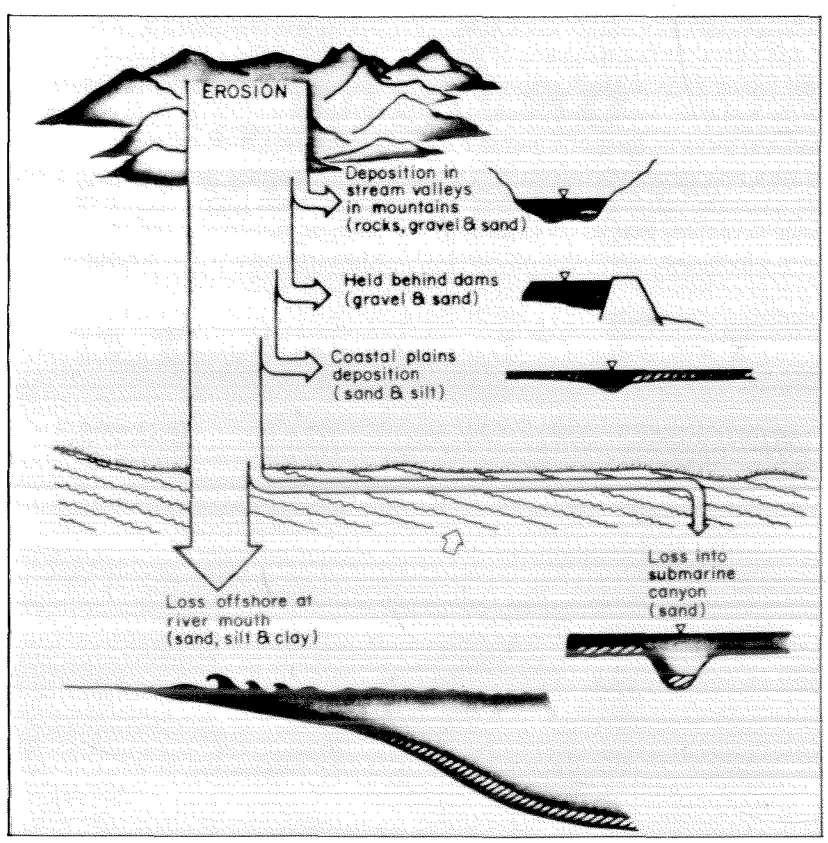
This new information on the differences in heat flux between Jupiter and Saturn is consistent with planetary scientists' observations and theories of the cooling history of the solar system, based on the idea that all the planets originated at the same time in a violent event. Pioneer's evidence gives scientists more confidence that their understanding is correct.

Pioneer 11 is now on its way out of the solar system into interstellar space. But Saturn is expecting other visitors. Voyager 1 is scheduled to arrive in November 1980 and Voyager 2 in August 1981. And a Saturn Orbiter Probe is proposed for the late 1980s or early 1990s. Although Saturn is not expected to be as "cooperative" or "photogenic" as Jupiter, all these closer pictures and experiments should reveal still more of the secrets of the solar system.

Sedimental Journey

Sediment moves. It washes down off the mountains of southern California in streams and rivers, forming large alluvial fans at the base of the mountains where the coarser material is deposited, and beaches, where many of the sand-sized particles end up at the shoreline. Still finer silt is carried offshore where it sinks in deeper waters. These are all natural processes of the environmental system.

But the presence of millions of people between the mountains and the coast in southern California has made it necessary to modify some of these natural processes by building dams for flood control and water conservation, plus harbors, piers, and breakwaters. Each year in this area hundreds of millions of dollars are spent by federal, state, and local agencies on sediment management to protect against property damage and human injury, while allowing for full use of natural resources and protecting the natural environment — all at the same time. In the past all these agencies have operated somewhat independently in their different jurisdictional responsibilities and without benefit of a clear, comprehensive description of the



A schematic drawing of the overall sediment flow from the mountains to the sea shows approximately how much of it goes where. Beach sand (lowest arrow extending right) is not a large percentage of the total. The small arrow pointing in toward the shoreline indicates the direction of the wave action.

This series of groins (or jetties) that reach out into the ocean were placed along the beach at Pacific Palisades to stop the movement of sand, and they now provide a good illustration of how the natural transport of beach sand works. Wave action piles up sand on the north side of the groins, depleting the beach to the south. The effects of this interference would be much more severe at Santa Monica beach immediately to the south, if it were not for substantial artificial nourishment of that beach.

natural system and the specific effects of human interference on the system as a whole.

That's why Caltech's Environmental Quality Laboratory, in collaboration with the Shore Processes Laboratory at Scripps Institution of Oceanography, embarked four years ago on a long-term, region-wide study of the problem, with EQL's director, Norman Brooks, and D. L. Inman of Scripps as principal investigators. Brent Taylor, also of EQL, is project manager for the study, which is officially entitled Sediment Management for Southern California Mountains, Coastal Plains and Shoreline.

The shoreline itself, however, is not the end of the line for the sand-sized particles deposited there by streams and rivers. Waves and currents continually transport the sand southward, forming and nourishing other beach areas until eventually the sand is lost from the beaches to offshore areas via submarine canyons. So the beaches must be constantly replenished. This natural system is dynamic and fluctuates widely and often unharmoniously; for example, in 1969 the Santa Clara River delivered 10 million cubic meters of shoreline sand, but in the following year only one-one-hundredth of that amount. Only over several years can any equilibrium be maintained, and when man jumps into this naturally "balanced" equation and fiddles with the sediment supply and wave actions, the beaches must ultimately suffer. Because of upstream dams and a harbor built during World War II, the beach at Oceanside has already been reduced to cobblestones.

The initial phase of the Caltech-Scripps study, currently nearing completion, intends to provide a geographically detailed quantitative definition of annual sediment movements under natural conditions throughout the coastal region and of the consequences of man's intervention in these movements.

The sediment management team has found that each year an average of more than 12 million cubic meters of sediment are eroded from upland areas between Point Conception, north of Santa Barbara, and the Mexican border. Of the 12 million cubic meters, 6 million are finer than .06 millimeters (silt and clay size), 5 million are sand-sized material, and 1 million are coarser than 2 millimeters. Under natural conditions, half of the 5 million cubic meters of sand is deposited on inland flood plains. The study indicates that human interference may have reduced the remaining half by as much as 40 percent; that is, from 2.5 million cubic meters of shoreline sediment delivery per average year to 1.5 million.

This reduction has been partially offset by artificial nourishment of beaches brought about by coastal dredging and redisposal of sand, for example, in Marina Del Rey in Los Angeles and Mission Bay in San Diego. In fact, the average artificial nourishment during the past 40 years has been roughly equal to the estimated natural supply — 2.5 million cubic meters per year — but distributed differently, as to time and place, from what would have occurred naturally. However, with increasing environmental concerns, it is doubtful that shoreline construction (harbors), which makes sand available for beach nourishment, will be permitted to keep up that pace in the future.

Study results suggest that we are probably entering a period when the full effects of human intervention will be increasingly felt — that is, there will be more and more beach erosion. So it is especially urgent that the agencies involved understand this natural system and cooperate to manage it carefully, to engineer an acceptable balance so that future generations will be able to enjoy the end product of the "sedimental journey" — sand beaches — without at the same time having to suffer the effects of its muddy onset.

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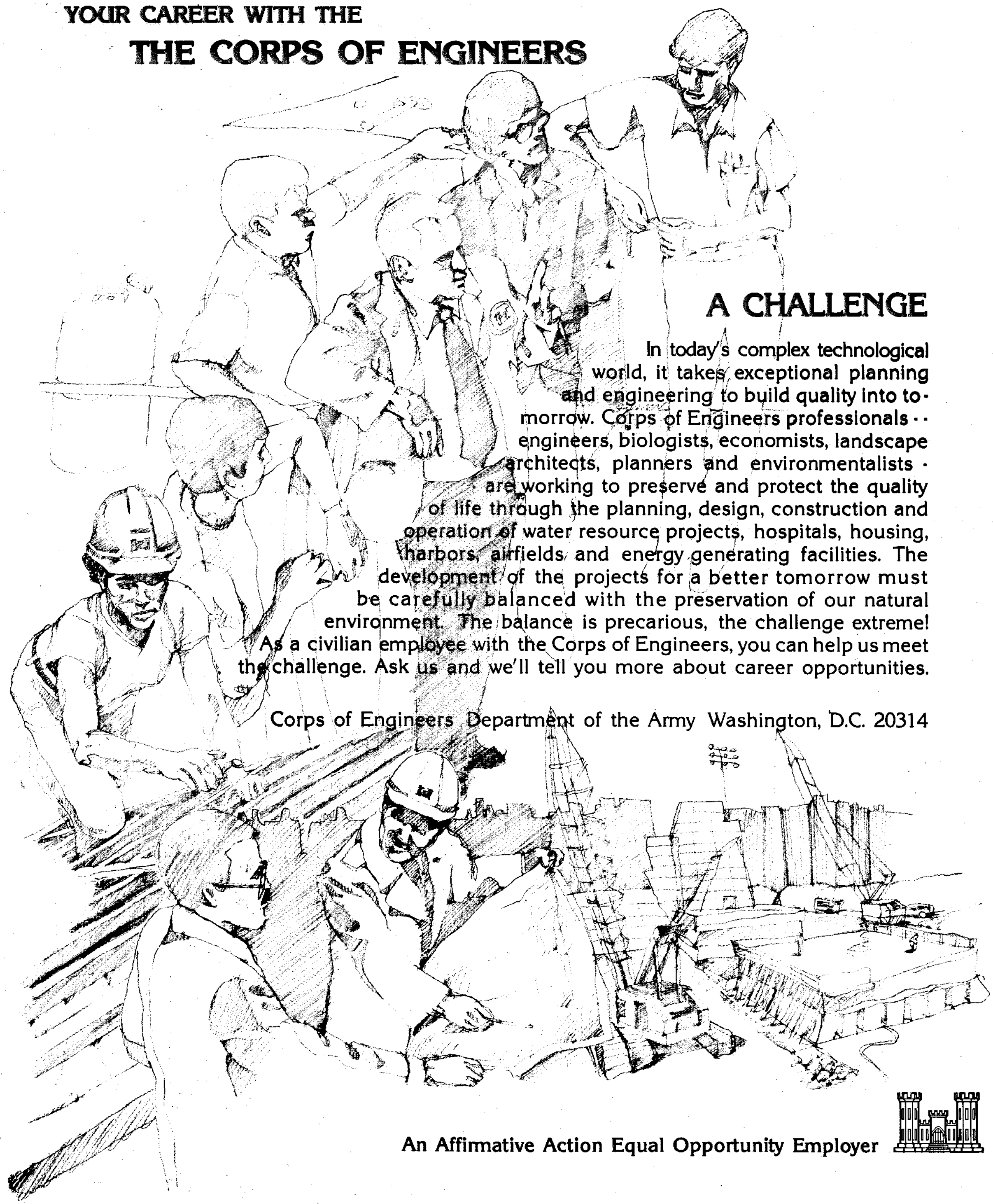

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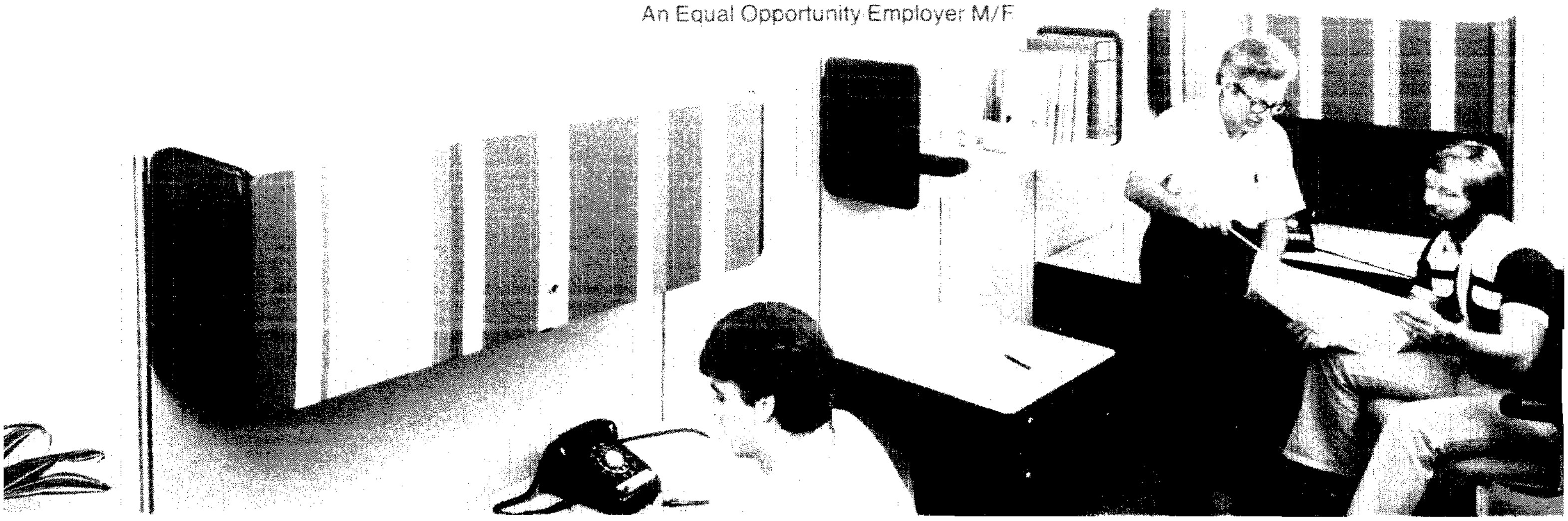

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