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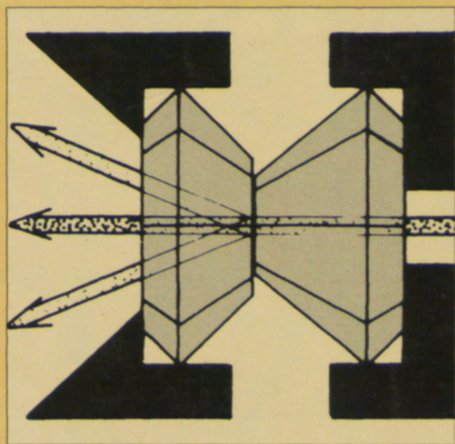

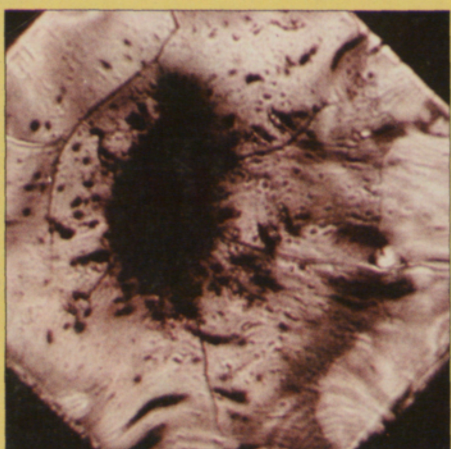

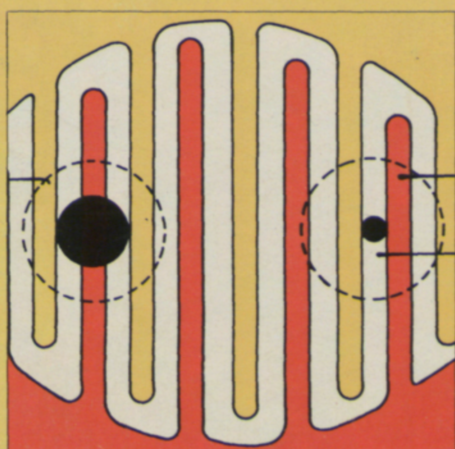

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MATERIALS AT ULTRAHIGH PRESSURES

IN THIS ISSUE

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Opposite: A transmission optical micrograph showing dislocations in a deformed grain of the mineral olivine.

Outside cover illustrations (clockwise): a diagram of a diamond anvil cell; olivine seen under an optical transmission microscope; a diagram of an interdigitated electrode with submicron spacing, used in high-pressure studies; a microscopic view of iron silicate that has been subjected to high pressure and temperature in a diamond anvil cell and has assumed different mineral forms in accordance with the pressure differential.

MEGABAR PRESSURES IN SUBMICRON VOLUMES

by Arthur L. Ruoff

The pressure in an ordinary automobile tire is about 3 bars, approximately three times atmospheric pressure. City water pressure may be 4 to 5 bars. The pressure at the deepest spot in the ocean is about 1,000 bars or 1 kilobar (kbar). Many commercial processes are carried on at pressures of 1 to 5 kbars; diamonds are synthesized at about 50 kbars. The pressure at the center of the Earth is about 3.7 million bars or megabars (Mbars). It is at pressures in the megabar range that the work of my research group is focused.

Under these extreme pressures, materials have properties very different from those they exhibit under ordinary conditions. If the material is a liquid, there can be an enormous increase in viscosity and a drastic change in the freezing point. A solid sometimes assumes a new, more condensed structure. New chemical compounds may form, or existing compounds may break up into their elements. Nonconductors become metals, and often these new metals are superconductors at low temperatures.

The industrial potential of this modern-day alchemy is enormous. For example, if pressure-induced superconductors prove to be metastable—if they can be kept in metallic form after the pressure is released—they could be used in many electrical and electronic applications. But current research is directed primarily to basic scientific studies and to the development of necessary techniques. Significant progress has been made in attaining ultrahigh pressures and in producing and examining new forms of materials. Our group at Cornell has had some exciting successes: we have made metallic xenon, for example, and we have converted sulfur, one of the best electrical insulators, to a metal. A new approach is to make use of unique new submicron fabrication and x-ray facilities at Cornell to create and examine materials in new forms.

HIGH-PRESSURE EFFECTS ON PHASE AND STRUCTURE

What happens to materials as a result of pressure? Essentially, the atoms are pushed closer together, drastically altering the macroscopic properties as well as the molecular structure.

The magnitude of viscosity change, for example, is difficult to conceive. A mixture of three parts methanol and one part ethanol increases in viscosity by a factor of 10 trillion (10^{13}) when a pressure of 100 kbars is applied. Under pressure, materials freeze at higher temperatures than they do under atmospheric conditions. Liquid hydrogen, for instance, freezes at 16°K at atmospheric pressure, but at 56 kbars, the freezing point is 300°K, about room temperature. A solid may change to a new structural form with a higher coordination number (the number of nearest-neighbor atoms or ions). In sodium chloride, for example, each sodium ion has six chlorine ions surrounding it at atmospheric pressure, but above a few hundred kbars each sodium is surrounded by eight chlorines. Materials scientists say that the compound has undergone a phase transformation from the sodium-chloride-type structure to the cesium-chloride-type structure.

The transformation of graphite to diamond is another example of a pressure-induced increase in coordina-

"The industrial potential of this modern-day alchemy is enormous."

tion number. In graphite, which is the equilibrium structure of carbon at atmospheric pressure, each atom has three nearest neighbors. Above about 14 kbars at room temperature, diamond is the equilibrium structure, and each carbon has four nearest neighbors. This may seem puzzling, for we know that both graphite and diamond exist at atmospheric pressure. The explanation is that diamond is metastable under ordinary conditions. A thermodynamicist would say that graphite has a lower free energy than diamond at room temperature and pressure; the carbon atoms in diamond would "like" to arrange themselves into the graphite structure and thereby lower their free energy. The rate of this rearrangement is slow, however: one need not worry about a diamond gem reverting to graphite. But if the temperature were raised substantially, say to 1,700°C, this reversion would occur rapidly.

The transformation of graphite to diamond at high pressure is the basis of a large industry: synthetic diamond production. In fact, most industrial diamonds are now produced synthetically. They are used for such diverse operations as grinding hard materials such as the turbine blades in a jet engine, cutting grooves in highways, scratching designs on Steuben glass, slicing silicon crystals into wafers, and drilling oil wells. In the United States, the General Electric Company has a major synthetic diamond plant in Columbus, Ohio. There are other synthetic diamond plants in France, Ireland, Japan, Russia, South Africa, and Sweden.

Silicon, both as an element and in compounds, also undergoes an increase in coordination number under high pressure. Normally silicon exists in silicate structures, as part of the $(SiO_4)^{-4}$ radical and has four nearest-neighbor oxygen atoms, but at a few hundred kbars, six-fold coordination occurs; this process is of enormous importance in geology. Elemental silicon shows an increase in coordination number from four to approximately eight at about 120 kbars; in the process, it changes from a semiconductor to a metal. Diamond, which has the same crystal structure as silicon, will probably transform to a metal at about 2 Mbars.

COMPOUND FORMATION AND DECOMPOSITION

Not only changes in crystalline structure, but also the formation of crystalline compounds can be accomplished under high pressure. Cubic boron nitride, for example, is a metastable material commercially made by a process similar to that used for diamond: ordinary BN is dissolved in liquid metal, pressure-treated, and then precipitated as the cubic form. But research now underway is showing how the cubic form can be produced at much lower pressures and in larger quantities by growing it from a solution containing boron and nitrogen compounds.

The opposite process—the decomposition of a compound into its elements—can also occur under high pressure. This happens with C_3S_2, a compound we have worked with in our laboratory. Our hope was that the carbon produced at high pressure and room temperature would be in the form of diamond. It wasn't; but had this process worked, we might have synthesized diamond at 15 kbars instead of the 50 kbars used in commercial practice.

A variation of decomposition under pressure is a reaction in which the original compound forms a different compound plus an element. Recently there has been much excitement about results suggesting that cuprous chloride exhibits unusual magnetic behavior (characteristic of superconductors) when it is subjected to high pressures. There is some evidence that the reaction taking place is $2CuCl \rightarrow CuCl_2 + Cu$.

TRANSFORMING INSULATORS INTO CONDUCTING METALS

At sufficiently high pressures, all semiconductors and insulators are expected to be metals (pure semiconductors at low enough temperatures are also insulators). For example, zinc sulfide, an excellent insulator, becomes metallic at about 150 kbars. The semiconducting III-V compound gallium phosphide becomes metallic at about 200 kbars. Mike Chan, a graduate student in my group, is looking at aluminum nitride; there is a theoretical prediction that it will transform to a metallic phase at 0.9 Mbar. An indication of the relative pressures needed for metallic transformation is given by the position of the elements in the periodic chart (see Table I).

Table I

METALLIZATION OF NONMETALLIC ELEMENTS

Groups

IIIb	IVb	Vb	VIb	VIIb	VIII
				H	He
B	C	N	O	F	Ne
	Si	P	S	Cl	Ar
	Ge	As	Se	Br	Kr
			Te	I	Xe
					Rn

There are two general rules about the pressure needed to transform the nonmetallic elements to metallic conductors: (1) in a given row of the periodic table, the required pressure increases from left to right; and (2) in a given column the transition pressure increases from bottom to top. Thus helium will require the most pressure. None of the first- or second-row elements have been made metallic; boron should transform at a modest pressure of a few hundred kbars, although the kinetics of the transition may make high temperatures necessary. The elements Si, Ge, P, As, Se, Te, and I all become metallic below 200 kbars, and all of these metals except iodine have been found to be superconductors at high pressure.

In our laboratory at Cornell, we have conducted high-pressure experiments with several of these nonmetallic elements. We have cooled iodine metal (at pressure) to 1°K with no sign of superconductivity. Currently Millard Baublitz, a student in my group, is attempting to study it at temperatures down to 0.3°K, but perhaps even that will not be low enough to produce superconductivity. In other work, we showed that sulfur, which is ordinarily an extremely good insulator, becomes metallic at room temperature at 300 kbars. And we found that solid xenon became metallic when pressurized to 320 kbars at 32°K. (Of the inert gas solids, radon should transform at the lowest pressure, but because it is radioactive, we chose not to work with it.)

We think that oxygen and hydrogen are exciting possibilities for future research. A metal transition in oxygen should require a pressure of about 1 Mbar. For hydrogen, a pressure variously estimated at 1.6 to 7 Mbars might be needed.

ATTAINING HIGH PRESSURES IN THE LABORATORY

There are two general rules for obtaining high pressures: (1) use the hardest substance known for the apparatus; and (2) create the pressure in the smallest volume possible. These criteria determine our laboratory technique.

Diamond is the stiffest and hardest material on Earth, with the highest yield strength. It has the same crystalline structure as silicon and germanium, but is about ten times stiffer and stronger. All three of these materials are brittle—tiny scratches on their surfaces will greatly decrease their fracture strength—and all three plastically deform if fracture is prevented. The bulk compressive strength of diamond is about 350 kbars, which is very high; the next strongest common material, sintered tungsten carbide, has a yield strength of 52 kbars (as determined by Prakash Panda, a graduate student, and me), and ultra-strength steels have yield strengths in the region of only 20 kbars. Anvils made of diamond would begin to yield at 500 kbars and could sustain a maximum pressure, when heavily deformed, of about 1 Mbar.

If truly perfect diamonds were available, much higher pressures could be attained. It has been predicted that the yield strength of perfect diamond would be 4.1 Mbars. But single crystals of diamond, regardless of their sparkle and clarity, are neither pure carbon nor perfect crystals; they contain about 1 percent of impurities, either in solution or as tiny precipitates, and they exhibit crystalline irregularities amounting to about 10^5 centimeters of dislocation line per cubic centimeter of material. (Dislocations are significant because plastic deformation occurs by motion of these line defects.) Large dislocation-free crystals of silicon can be grown, and it is not inconceivable that this could be accomplished with diamond. But at the present time, the best alternative is to use a diamond of very small size; if small enough, it will be free of dislocations. Such a region must be about 10 microns (μm) in each dimension (1 μm = 10^{-6}m = 10^{-4}cm).

Accordingly, the technique we use to obtain very high pressures is to press

Figure 1

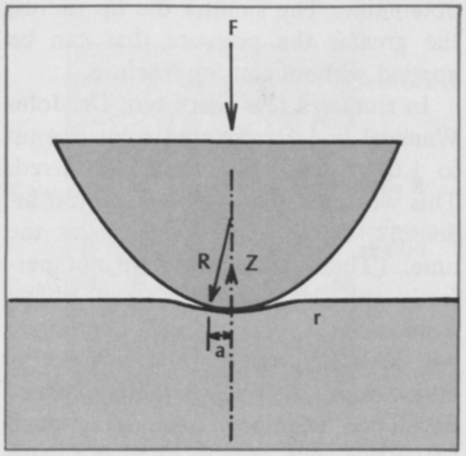
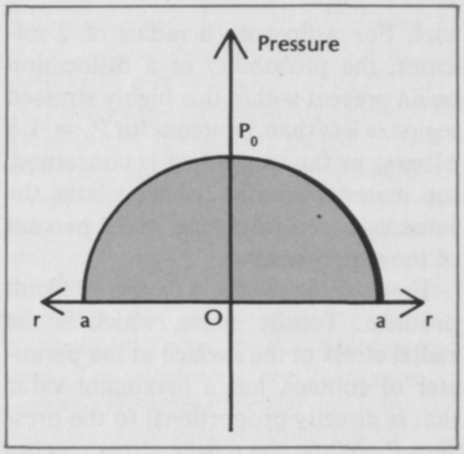


Figure 1. A schematic of the spherical indentor–flat anvil pressure-generating system. A force F is applied on the indentor, which has a spherical tip of radius R. Pressure is exerted over a contact area of radius a, with a maximum value at the center. The smaller the tip, the larger the pressure attained: with tip radii in the micron range, megabar pressures can be achieved at the center.

Figure 2. The pressure distribution of the system shown in Figure 1. The maximum pressure, P_o, is produced at the center of the area of contact, where r=0 and z=0. The area of contact has a radius a.

Figure 2



a tiny diamond with a spherical tip—the indentor—against a flat diamond, as shown in Figure 1. This results in a contact pressure distribution, as shown in Figure 2, with a maximum, P_o, that can be calculated from elasticity theory. The equation we use was formulated by Hertz:

$$P_o = (3/2)^{1/3} \pi^{-1} (E/1-\nu)^{2/3} R^{-2/3} F^{1/3}$$

where E is Young's modulus, ν is Poisson's ratio, R is the initial tip radius, and F is the applied force. This shows that the maximum pressure, P_o, is proportional to the applied force and inversely proportional to the radius of the indentor tip.

To understand the eventual failure of the diamond, we must consider the shear stress, which causes yielding by dislocation motion, and also the tensile stress, which causes fracture.

The shear stress is a maximum along the axis of revolution at a distance of about $a/2$ from the contact point (see Figure 2), and falls to about a quarter of this value on a spherical surface of radius *a* centered at the point of contact. For a tip with a radius of 2 microns, the probability of a dislocation being present within this highly stressed region is less than 1 percent for $P_o = 1.8$ Mbars: as far as yielding is concerned, the material should behave about the same as a perfect crystal in 99 percent of the experiments.

Fracture presents a more difficult problem. Tensile stress, which is the radial stress at the surface at the perimeter of contact, has a maximum value that is directly proportional to the pressure P_o. When the tensile stress reaches a certain critical value—the fracture strength—a ring crack forms. (The actual shape of the ring crack is determined by the way in which the cleavage planes intersect the surface.) This limits the maximum value of P_o. Happily, there is an important size effect that helps out, however. It was discovered by Auerbach in 1890 that when a steel bearing is pressed against glass, the fracture strength of the glass increases as the tip radius decreases; we have found that this law applies to diamond over a wide range of tip radii, from 2,000 microns down to the smallest obtainable. The smaller the tip radius, the greater the pressure that can be applied without causing fracture.

In studies a few years ago, Dr. John Wanagel and I registered pressures up to 1.6 Mbars before failure occurred. This work was done with 2-micron indentors, the smallest available at the time. (These indentors were not perfectly spherical; if their actual shape were taken into account, the pressure we achieved would be calculated as larger than 1.6 Mbars.) We have since developed techniques for making much better tips, with radii as small as a tenth of a micron. Dr. Dan Golopentia and I hope to report soon on the results of tests on these tips, which provide a means of checking theoretical predictions.

WORKING WITH SAMPLES IN THE DIAMOND CELL

A sample of material we wish to study under high pressure must be introduced as a very thin film between the flat diamond anvil and the indentor. If the film is sufficiently thin, the pressure distribution will still be given by our basic equation relating maximum pressure, P_0, to tip radius and applied force. The film may be introduced by vapor deposition, by sputtering, or by evaporation from solution. Very thin samples can also be prepared by thinning a bulk sample by grinding, polishing, and etching.

The pressure attained in an experiment is calculated directly from the Hertz equation. Since this expression includes a constant elastic modulus (E), it depends on the assumption of linear elastic behavior of diamond, an assumption that has been justified experimentally. The reliability of the pressure calculation has been verified up to 0.5 Mbar by a direct measurement using Newton's rings (an interference technique), and is considered applicable to about 2 Mbars. Other proved methods of determining high pressure also depend upon the assumption of linear behavior; for example, a measurement based on a shift in the ruby fluorescence peak (see the article in this issue by William Bassett) assumes a linear relation to pressure, and the method is known to be accurate at least to pressures of 100 Kbars.

Since one of the effects of high pressure in which we are most interested is the transition from nonconductor to metal, we must be able to measure changes in electrical resistance. We have developed two techniques to achieve this. By either method, the measurements are taken in a tiny area at the center of the sample, where pressure is near maximum. We call one technique the coated metal film method, and the other the interdigitated electrode method.

In the coated film method, thin films of metal are sputtered onto the highly polished diamond anvil and the diamond indentor, and leads are attached to each. The sample is placed on top of the metal film on the anvil, and the indentor is pressed against the sample. If the sample undergoes a transition to metal, this occurs in the region of highest pressure, along the axis of the indentor, so that resistance measurements pertain primarily to the first material to transform. This method has been used successfully in our laboratory, but it has one shortcoming: if the indentor were to punch through the specimen, a short would occur, and this would be difficult, as a rule, to distinguish from a transition. To avoid this problem, we invented the second method.

The interdigitated electrode system is diagrammed in Figure 3. This technique, which was developed by Kam-Shui Chan and me, not only prevents electrical shorting, but also eliminates the difficult problem of positioning the indentor precisely so that the tip makes contact between the electrodes. (This is necessary to ensure that the electrodes measure the point of highest pressure, where the transition to metal occurs first.) With the interdigitated system, the indentor tip can be positioned anywhere in the electrode area, since the electrodes are fabricated as grids of seventy-five or more electrode fingers.

Of course, the use of very small tips —needed, as explained, to permit the attainment of very high pressures—requires comparably small electrodes. The grids we use are produced by photolithography in Cornell's new National Research and Resource Facility for Submicron Structures (see the April 1978 issue of this magazine). The width of each finger (d in Figure 3) was 6 microns in the first experiments we carried out. In the work on xenon, d was 3 microns, and we are working to reduce the spacing to 0.6 micron using projection lithography. We are also beginning to work with electron beam lithography, which is capable of producing an even finer pattern, and we hope later this year to be able routinely to make electrodes with a width of 0.1 micron.

The electrodes that we have used so far are nickel and are 350 Angstroms thick; in the future, other materials will be used for electrodes for different applications.

Figure 3

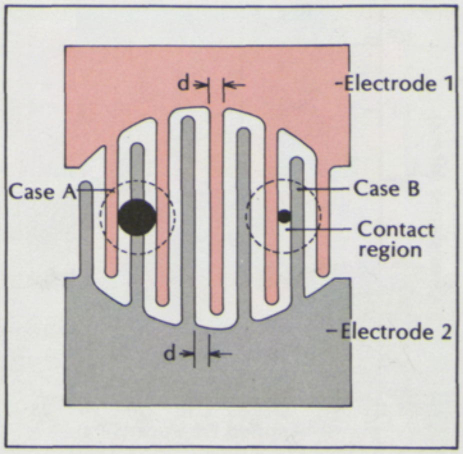


Figure 3. The nonshorting interdigitated electrode system for resistance measurements in very small areas. This assembly is placed on the diamond anvil and covered with a film of nonconducting sample, and then the indentor tip is pressed against it from above. If a transition to metal occurs, the maximum size of the conducting area is determined by the spacing between the electrode fingers and their width (d); such areas are indicated in the sketch by black circles corresponding to two possible indentor positions. Finger diameters can be made as small as a fraction of a micron. This system, developed in Professor Ruoff's laboratory, offers the advantage that the indentor can be positioned anywhere in the interdigitated area. The electrodes are fabricated in Cornell's National Research and Resource Facility for Submicron Structures.

Once the electrodes are in place, electrical leads are attached to the anvil base. Then the sample is deposited on the anvil. Finally, the indentor is pressed against the sample-electrode-anvil assembly, and contact is established over the region shown by the dashed circle in Figure 3. When the insulator-to-metal transition pressure of the sample is reached, the newly formed metal closes the circuit. The metallic region is represented in the figure by two solid circles, representing two extremes of possible indentor location. The center pressure will be different for these two cases; but if the finger widths and spacings are very small, the pressure at which the transition is observed will approach P_o.

EXPERIMENTAL RESULTS WITH OUR APPARATUS

Our diamond indentor–diamond anvil system has enabled us to make some interesting studies of what happens to various materials under extreme pressure.

One of the substances we investigated is aluminum oxide, of interest because early work at the Moscow High Pressure Institute had indicated a metallic transition at 0.4 Mbar. We did not observe a transition to a conducting phase, however, at pressures up to 1.2 Mbars. It should be noted that an electrical short would give the appearance of an insulator-to-metal transformation. Had we observed a sharp resistance drop, we would have used our nonshorting interdigitated-electrode method to confirm that a transition had actually taken place. The results we obtained demonstrate the necessity of ensuring against

Figure 4. Representative experimental results for the determination of the pressure at which zinc sulfide transforms to a metal. The transition is detected in the diamond-anvil cell as a drop in resistance. These experiments established that the transition occurred at an applied pressure of 14.0 ± 0.5 GPa (1GPa = 10 kbars); a value of 15.0 ± 0.5 GPa has been obtained on the ruby scale. A control experiment, in which no sample was present, showed no resistance drop.

Figure 5. Experimental results showing the creation of metallic xenon. Transitions from insulator to conductor were observed as drops in resistance (as measured on a Keithley 160B multimeter). The temperature was 32°K and the interdigitated electrode system was used in the measurements. The readings show a drop in resistance by a factor of 10^4 to 10^5, occurring at about 33 GPa (or 330 kbars). This work was done by David A. Nelson, Jr.

Figure 4

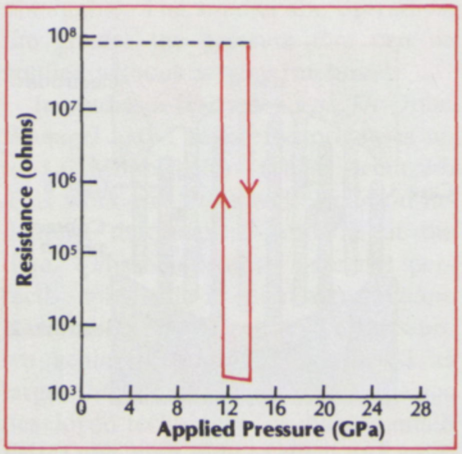
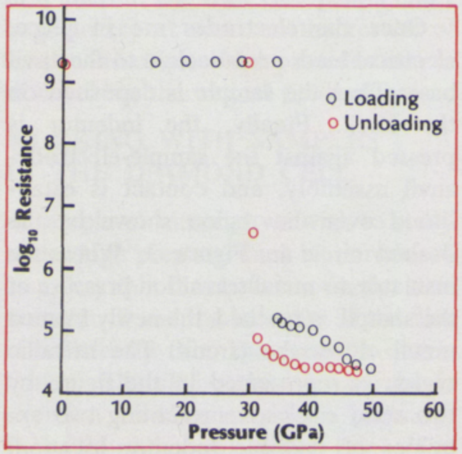


Figure 5



electrical shorting in high-pressure resistance measurements.

Using our interdigitated electrode technique, we detected a metallic transition with zinc sulfide (see Figure 4). This was the first observation of the transition in which pressures were measured by a primary method.

Our work with sulfur, in which we produced a transition to metal, revealed another interesting property: resistance was found to drop continuously as the pressure increased, rather than sharply as in most experiments. It appears that in sulfur the band gaps, and therefore the metallic behavior, vary linearly with pressure. This summer we plan to look for superconductivity in sulfur. Recent reports in the literature suggest that peculiar effects are involved and we are anticipating experiments of great interest.

For our research with xenon, we developed special techniques for handling gaseous samples. We introduced the gas into an evacuated chamber containing the anvil, and cooled it by means of liquid helium flowing through a supporting plate. The thickness of the xenon film condensed on the anvil was measured by a quartz thickness monitor, which uses quartz crystals on the cold plate—one crystal adjacent to the diamond anvil and the other in a permanently evacuated chamber. Results for a representative experiment, showing the transition from insulator to conductor, are given in Figure 5.

We have also studied the electrical behavior of ice at 78°K in the same apparatus with the same electrodes and indentors. We found that ice remains an insulator to 0.72 Mbar, the highest pressure used.

EXPERIMENTS UNDERWAY AND PLANNED

Current and future work will further improve the experimental techniques and equipment, and explore the high-pressure properties of additional materials.

We are continuing to develop tinier tips in order to achieve higher pressures; the ultimate static pressure attainable by use of diamonds will be known soon. Tinier tips will require smaller electrodes, and fabrication techniques for electrodes will also be refined. Three students will be working on these problems.

A special cell that can be used at temperatures as low as 2°K and with loads as small as 10 grams has been completed and is now being tested. Provided that the diamonds do not fail, this cell should produce a pressure of 2.4 Mbars with a load of 22 grams and a 1-micron indentor tip.

We also have an interesting piece of work in progress which uses a kind of diamond cell developed at the National Bureau of Standards. Here we are using

A new diamond indentor–anvil system in Professor Ruoff's laboratory will be used at temperatures as low as 2°K. Researchers involved in the experiments include (left to right) Robert Terry, high-pressure technician; Dan Golopentia, senior postdoctoral associate; and Volker Arnold, high-pressure technician. The diamonds and the load cell for measuring the force are in the cylinder just above the bench top.

an x-ray technique called Energy Dispersive X-ray Diffraction to study the crystal structure of the new phases produced. This technique has been used in earlier work at Cornell to look at the high-pressure structure of silicon, and is currently being used to study the high-pressure phase of gallium arsenide. With the high-energy x-ray source now available, experiments take a week or more to perform, but we hope soon to be able to use x rays of much higher energy from the Cornell High Energy Synchrotron Source (CHESS) when construction of this facility has been completed. The shorter time required to gather data—perhaps minutes instead of weeks—will enable us to study the kinetics of transformations occurring at high pressure.

Of the materials we hope to study, oxygen and hydrogen have high priority. We will also continue our studies of metallic iodine, sulfur, and xenon, to see whether we can detect superconductivity. Other materials of considerable interest are methane, ammonia, nitrogen, and, of course, diamond itself.

We are also beginning to examine the effects of high pressure on the conductivity of a polymer, polyacetylene. This material, which has fibrils containing one-dimensional chains, conducts electricity much better along the chains than perpendicular to them (it has a band gap of about 1.4 eV and can be doped to be a p-type or an n-type semiconductor), and high-pressure studies may elucidate the conductivity mechanism. Perhaps we will convert this semiconducting polymer into a metal; conceivably, however, high pressure will decompose it.

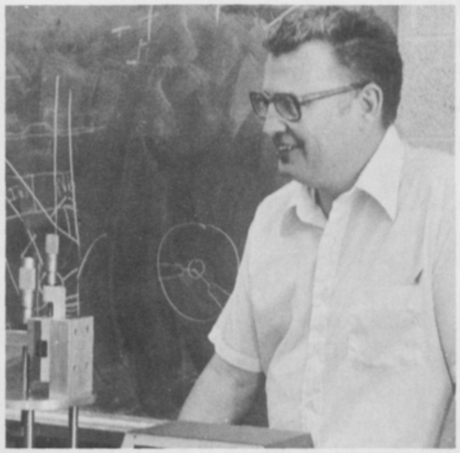
LOOKING AHEAD TO HIGH-PRESSURE POSSIBILITIES

Since high pressure drastically alters the characteristics of materials, it raises hopes that radical new technologies may become available. For example, superconductivity effects that occur at high pressures look attractive as transmission costs increase. An idea that is particularly enticing to many people is the formation of metallic hydrogen, which could be used for rocket fuel or as pellets for energy production in fusion reactors. NASA (which is supporting much of the high-pressure research we are conducting at Cornell) is interested in this possibility.

I am often asked whether I believe that metallic hydrogen will be metastable—that is, whether it will persist at ordinary pressures if kept at low temperatures. My answer is and has been: No. My reason is that the metallic state involves long-range forces, and the only examples of metastability involving large energy differences (0.1 eV per atom, say) involve short-range covalent bonds. Moreover, the degree of "unhappiness" of metallic hydrogen—expressed as a free energy of 4 eV per atom at zero pressure—constitutes a tremendous driving force to return to the molecular state. I could be wrong, but I'll be very surprised if I am. I am also asked whether I think hydrogen will be a superconductor at relatively high temperatures (above 100°K and possibly at room temperature), as some theorists have predicted. Again, I have to say no. Here my reason is that the theorists have calculated the electron behavior of hydrogen metal on the assumption of a static lattice; but in hydrogen the ions (protons) are very light and have appreciable kinetic energy. I expect that accounting for this properly will drastically alter the theoretical predictions.

If I were asked to suggest what will be the highest transition temperature of an element to a metal, I would say that it may be as high as 30°K at pressures of a couple of megabars, and that the metal will be carbon, nitrogen, or oxygen.

Much is still unexplored and unknown in the realm of ultrahigh pressure. There is a long way to go from millions of atmospheres of pressure exerted over dimensions of less than a millionth of a meter to ultrahigh pressures of practical use. But this is partly what makes high-pressure studies an exciting field of research: the possibilities for innovative work are great, and the potential for discovery and application is enormous. Remarkable results are anticipated, hoped for—or perhaps still unimagined.



Professor Arthur L. Ruoff is the director of the Department of Materials Science and Engineering and is the Class of 1912 Professor of Engineering. He is known especially for his research in high-pressure phenomena: in his ongoing effort to produce metallic hydrogen, he has developed techniques of applying pressures as high as 1.4 million atmospheres. Ruoff's recent success in producing metallic xenon was announced by the National Aeronautics and Space Administration as an important step toward the goal of producing metallic hydrogen.

Ruoff joined the faculty here in 1955 after earning the B.S. degree at Purdue University and the Ph.D. in physical chemistry at the University of Utah. At Cornell he has served as graduate faculty representative for materials science and engineering, and he is a member of the graduate Fields of Applied Physics and Geological Sciences. He has twice served on the executive committee of the University's Materials Science Center, and currently is active in the National Research and Resource Facility for Submicron Structures, both as a researcher and as a member of the program committee. Outside the University he serves as a consultant to numerous industries and laboratories on high-pressure phenomena, and to several universities on techniques of multi-media instruction, a teaching method he has developed in classes here.

His honors include a National Science Foundation Senior Science Faculty Fellowship, and the 1967 Western Electric Fund Award, presented by the American Society for Engineering Education for excellence as an educator. He is a fellow of the American Physical Society and has been named Engineer of Distinction by the Engineers Joint Council.

IN THE DIAMOND ANVIL CELL

Mineral Samples at High Pressure Give Information on Earth's Interior

by William A. Bassett

Studying the mineralogy of Earth's interior is like putting together a jigsaw puzzle. Some of the pieces come from observations by geophysicists. Others are obtained from laboratory measurements of minerals at the high pressures and temperatures characteristic of Earth's deep layers. Piece by piece, a picture of our planet's interior emerges.

The ability to obtain direct information about the constitution and nature of Earth's interior has been greatly improved in the past few decades through development of the tools of geophysics. Seismographs accurately measure sound waves generated by earthquakes on the Earth's far side, and yield information about the physical states of the various regions the waves traverse on their passage through the Earth. Sensitive surface measurements of gravity, heat flow, and magnetism give clues to conditions in the interior. Satellite observations showing subtle variations in Earth's shape and motion contribute to our understanding of the whole planet. In addition, plate tectonic theories have helped shape our perception of Earth processes. We have come to realize that many of the rocks found on the surface are, in fact, samples of Earth's mantle, and as an appreciation of these rocks has grown, Earth scientists have developed a better understanding of their importance.

But direct geophysical observations, valuable as they are, give an incomplete picture without knowledge of the properties of minerals at the pressures and temperatures that exist within the Earth's interior. It is here that experiments in high-pressure mineralogy play an important role, providing information needed to interpret geophysical measurements. Suppose that geophysical observations tell us that the rocks at a particular depth have a certain density, and conduct sound waves at a certain velocity. In order to use those data to identify the rock, an investigator must know which minerals exhibit those properties under the same conditions. Such experiments require techniques for subjecting mineral samples to very high, measured pressures and temperatures in the laboratory, and for determining their physical properties under those conditions. Development and application of such techniques have been among the goals of high-pressure research at Cornell.

EXPERIMENTAL MINERALOGY AT HIGH PRESSURES

Although there are many ways of producing pressure, they all fall into three broad categories: squeezing, hitting, and submerging (see Figure 1).

The first of these, squeezing, is the basis of most of the laboratory techniques for producing static high pressures. Experiments using such techniques have certain elements in common: a strong frame for the apparatus, a device for generating a force, anvil faces or container walls that push against the sample or against a medium containing the sample, and, finally, the sample itself.

The second category, hitting, includes dynamic experiments in which the momentum of a missile and the inertia of its target, the sample, combine on collision to generate high pressures; the sample remains at high pressure for a very short time, usually only microseconds.

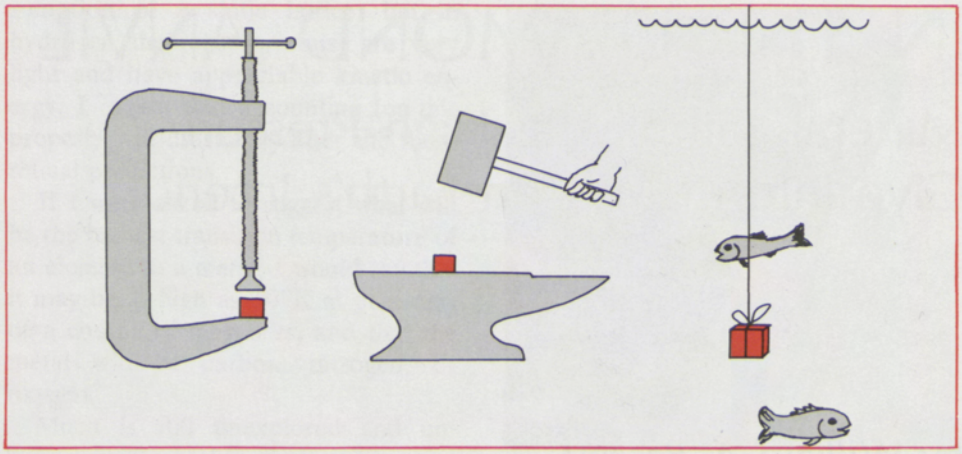


Figure 1

Figure 1. The three principal mechanisms for pressure generation: squeezing, hitting, and submerging.

Figure 2

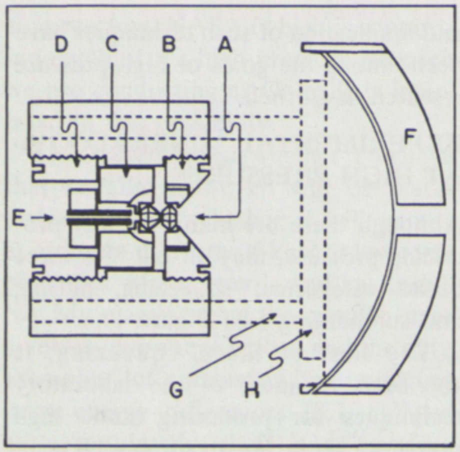


Figure 2. A cross section of one of the basic designs for a diamond cell. Parts include: A—diamond anvils; B—stationary piston; C—sliding piston; D—driver screw; E—collimator; F—film cassette; and G, H—mounting bars.

The third method, submerging, results simply from gravitational force acting on a fluid. This is, in fact, the mechanism by which the pressures on and within the Earth are produced—pressures of one bar (one atmosphere) on the surface, approximately one kilobar (one thousand atmospheres) at the deepest point in the ocean, and hundreds of kilobars in the deep mantle. This mode of pressure generation requires neither strength nor inertia; the high pressures exist regardless of the state of the material and, for example, would be present in the Earth's interior even if the planet were liquid. Submersion is not a practical means of producing very high pressures in the laboratory, however. The achievement of pressure levels comparable to those in the Earth's interior would require a mass of material equal to that of Earth itself.

A basic property of matter is that different forces are dominant at different scales of mass. On the scale of the Earth, subatomic forces (which are responsible for the strength of materials) are less important than gravity. On the smaller scale of our everyday experiences, however, interatomic forces play a very major role. With a laboratory "squeezer" an investigator can take advantage of the strong interatomic forces to reproduce the pressures developed by gravational force within the Earth. This is the approach I have taken in my experimental work to determine the properties of minerals under mantle conditions.

SMALL-SAMPLE STUDIES IN THE DIAMOND CELL

An important feature of the apparatus used in these studies is its small size. This benefits the investigator in several ways. Scaling down has the effect of increasing the strength of a material because of the greater importance of interatomic forces. Also, since pressure is defined as force divided by area, a decrease in area rather than an increase in force can be used to raise the pressure. In our cell, only a modest method for producing the force is required—a simple screw is sufficient. An additional advantage is that small parts, such as anvils, can be made more perfect than larger ones and can be fashioned from exotic materials such as diamond, which is the hardest substance known. All these advantages are embodied in the diamond cell (see Figure 2).

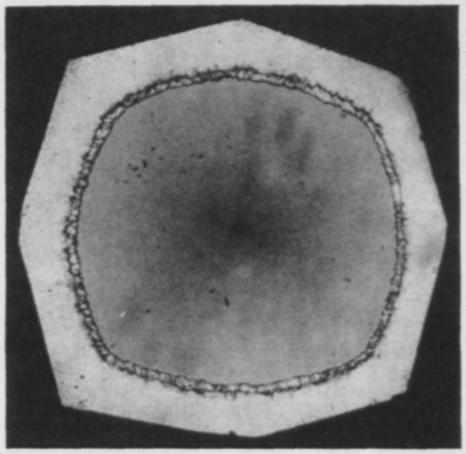
The diamond cell was developed by a group at the National Bureau of Standards in 1959. It is basically a very simple mechanism. At the heart of it are two gem-quality, flawless, single-crystal, faceted diamonds arranged with two opposing flat parallel faces. These are the high-pressure anvils, produced from faceted gem diamonds by cutting and polishing a face on the culet point of each stone. For an experiment, a sample is placed between the flat faces and the anvils are driven together to produce pressure in the sample. One of the anvils is fixed and the other is mounted on the end of a sliding piston driven by a screw. In some cases, the sample is simply inserted between the anvil faces; in other experiments, the sample is placed in a hole drilled in a metal foil and the foil is inserted between the diamond faces. With the latter technique, it is possible to place a liquid in the hole and a crystal in the liquid, thus achieving the production of a perfectly hydrostatic pressure on the crystal when the anvils are tightened. One experimental requirement is that the samples must be extremely small—ours range from 10 to 100 micrometers across and 5 to 100 micrometers thick (a human hair is about 75 micrometers in diameter).

One can get a surprising amount of information from such a tiny sample, however, for a large number of analytical techniques can be used in conjunction with the diamond cell. Optical observations can be made by placing the cell on the stage of a microscope and looking at the sample through the diamonds. X-ray diffraction studies can be made by passing an x-ray beam through the diamonds. Electrical resistance can be measured by placing small wires within the sample. Light scattering can be used to investigate the elastic properties of a single crystal by sending a laser beam through the diamonds and determining how it is scattered by sound waves in the crystal. The lower limit of sample size is determined by the analytical technique—we use the smallest sample from which we can get information. Actually, every high-pressure experiment is a compromise; the smaller the sample, the higher the pressure that can be achieved, but the harder it is to make observations.

The diamond anvil cell containing a sample that has been subjected to high pressure and sometimes high temperature can be removed and examined by a number of analytical techniques. Here a unit containing the cell has been placed on the stage of a microscope.

Figure 3. Silver iodide under pressure in the diamond cell as it appears when viewed through one of the diamond anvils. The highest pressure, about 10 kilobars, is at the center; an intermediate phase, between 4 and 5 kilobars, exists as a ring; the low-pressure phase, below 4 kilobars, forms around the outside of the ring. The sample shown in the micrograph is about 0.5 millimeter across.

Figure 3



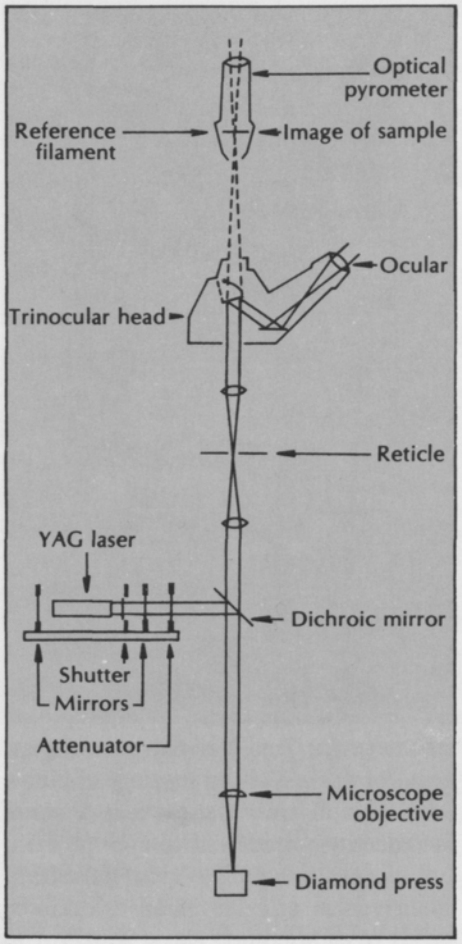
The distribution of pressure within a diamond cell is demonstrated in Figure 3, a photograph of silver iodide under pressure. Since sample material extrudes from the edges of the anvils, there is more material trapped toward the center of the anvil area, where pressure is therefore greatest. The silver iodide undergoes phase transitions, clearly discernible in the figure, according to pressure distribution. The highest pressure phase, corresponding to about 10 kilobars, is at the center; between 4 and 5 kilobars there is a ring

Figure 4. The laser system for generating high temperatures in a sample under pressure in the diamond cell. The optical pyrometer measures the temperature.

of the intermediate pressure phase; and the lowest pressure phase, less than 4 kilobars, is outside the ring.

Silver iodide goes through phase transitions almost instantaneously when pressure is applied. The silicates that make up the Earth's mantle do not, however, and in order to study the high-pressure phases of these minerals in the diamond cell, it is necessary to heat the samples as well as subject them to high pressures. The technique we have developed to achieve this simultaneous heating is to focus an infrared beam from a YAG laser through one of the diamonds onto the sample under pressure. Some of the same principles hold for the production of temperature as for the production of pressure; for example, for a given input of power, the smaller the sample, the easier it is to achieve high temperatures. In our diamond cell, 10 to 20 watts of power is sufficient to raise the temperature of the very small sample to 2,000°C. The system, diagrammed in Figure 4, has been used successfully to study the phase relations in silicates under various high-pressure and high-temperature conditions.

Figure 4



THE MEASUREMENT OF PRESSURE AND TEMPERATURE

Pressure achieved in the diamond cell can be measured in two ways. One method is to mix a sample with sodium chloride and then subject the mixture to pressure. An x-ray diffraction pattern of the sodium chloride while it is at high pressure yields information about the interatomic distances in the salt, and from the known compressibility of sodium chloride it is possible to calculate the pressure. The other technique involves placing a small chip of ruby in the diamond cell along with the sample. While the material is under pressure, an intense beam of blue light from a laser is used to excite fluorescence in the ruby chip, and since the wavelength of the ruby's red fluorescent light is pressure-dependent, spectroscopic measurement of the emitted light can be used to calculate the pressure. This second method is much faster and simpler than the sodium chloride procedure, and has become more popular with diamond-cell users.

Temperature is measured by optical pyrometry. During laser heating, the sample becomes incandescent and the brightness of the light from the incandescent sample is used to measure its temperature. The optical pyrometer shown in Figure 4 compares the intensity of the light from the sample with the intensity of light given off by an internal filament.

STUDYING EARTH'S MANTLE IN THE LABORATORY

The Earth's mantle, which extends (see Figure 5) from the bottom of the crust (6 to 50 kilometers deep) to the core (2,900 kilometers deep), consists principally of iron-magnesium silicates. One of the most important applications of the diamond cell has been to study the crystal structures of high-pressure phases of these silicates and to determine the pressure-temperature range over which they are stable. In addition, the diamond cell has been used to study the properties of these phases. Properties that have been studied so far include electrical conductivity, optical absorption, compressibility, elasticity, and chemical behavior.

Stability fields and crystal structures

Figure 5

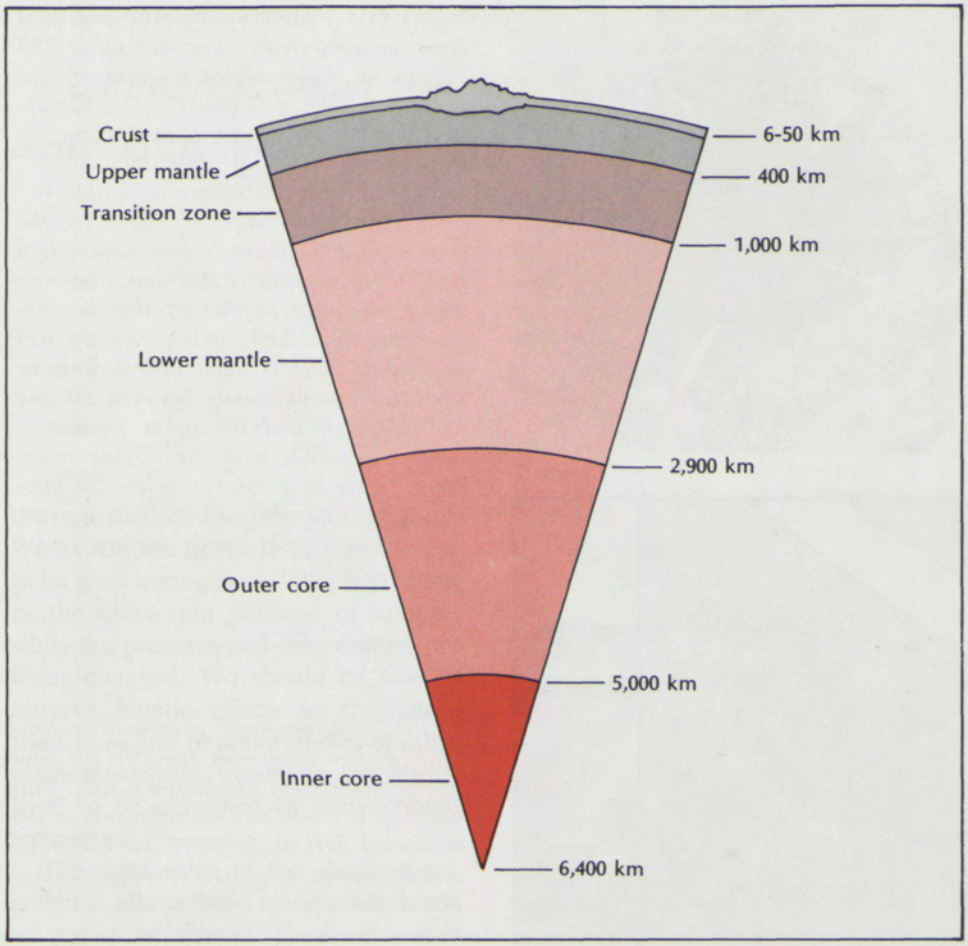


Figure 5. The interior of the Earth is stratified, with the light silicates of the crust at the top, and the hot metal core at the center. In between is the mantle, composed primarily of magnesium and iron silicates. The behavior of materials within the mantle has become of interest to geologists seeking to define the processes beneath such surface phenomena as volcanism, earthquakes, seafloor spreading, and continental drift.

of the high-pressure, high-temperature phases are determined by subjecting samples to different pressure and temperature conditions in the diamond cell, and then analyzing them by x-ray diffraction. The procedure is to place a sample under pressure between the diamond anvils, measure the pressure by one of the techniques described, heat the sample by means of the infrared laser beam, and then, after cooling and unloading, study the treated sample by x-ray techniques. Nearly all the high-pressure forms of silicates persist after cooling and unloading (see Figure 6). A proposed pressure-composition map of the stability fields for the various phases of the olivine compositions, Mg_2SiO_4-Fe_2SiO_4, is shown in Figure 7. Temperatures were in the range of 1,000° C to 1,500° C. From these relationships, and those for silicates of similar composition, it has been possible to establish that at the pressure and temperature conditions of the lower mantle (below one thousand kilometers), the phases that are stable are $(Mg,Fe)SiO_3$ in the perovskite structure plus $(Mg,Fe)O$ in the periclase structure. These two structures represent very efficient packing of the atoms.

Investigations of the optical and electrical properties of the various high-pressure, high-temperature phases of the iron-magnesium silicates have shown that these phases absorb light and conduct electricity better as pressure increases. Such findings have important implications for the development of models of the Earth's interior. For example, it was thought at one time that a significant mechanism of heat transfer within the Earth might be direct radiation through transparent minerals in the mantle, but the experimental work on the physical properties of silicates shows that this cannot be the case.

Many of the results discussed here were obtained by my former students Ho-kwang Mao, Lin-gun Liu, and Li-chung Ming, who have gone on to further work in the application of diamond-cell measurements to problems of geophysics. Current work is being carried out by John Hrubec and Pouyan Shen in recently refurbished quarters in Olin Hall.

Figure 6

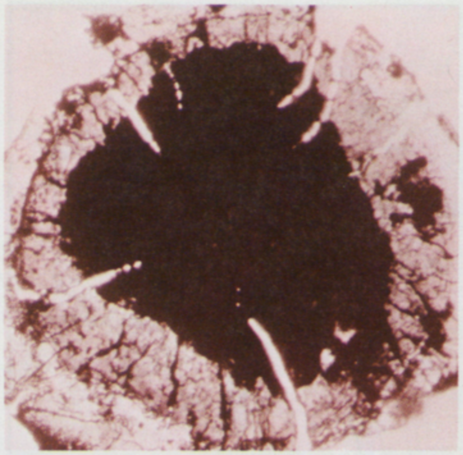


Figure 7

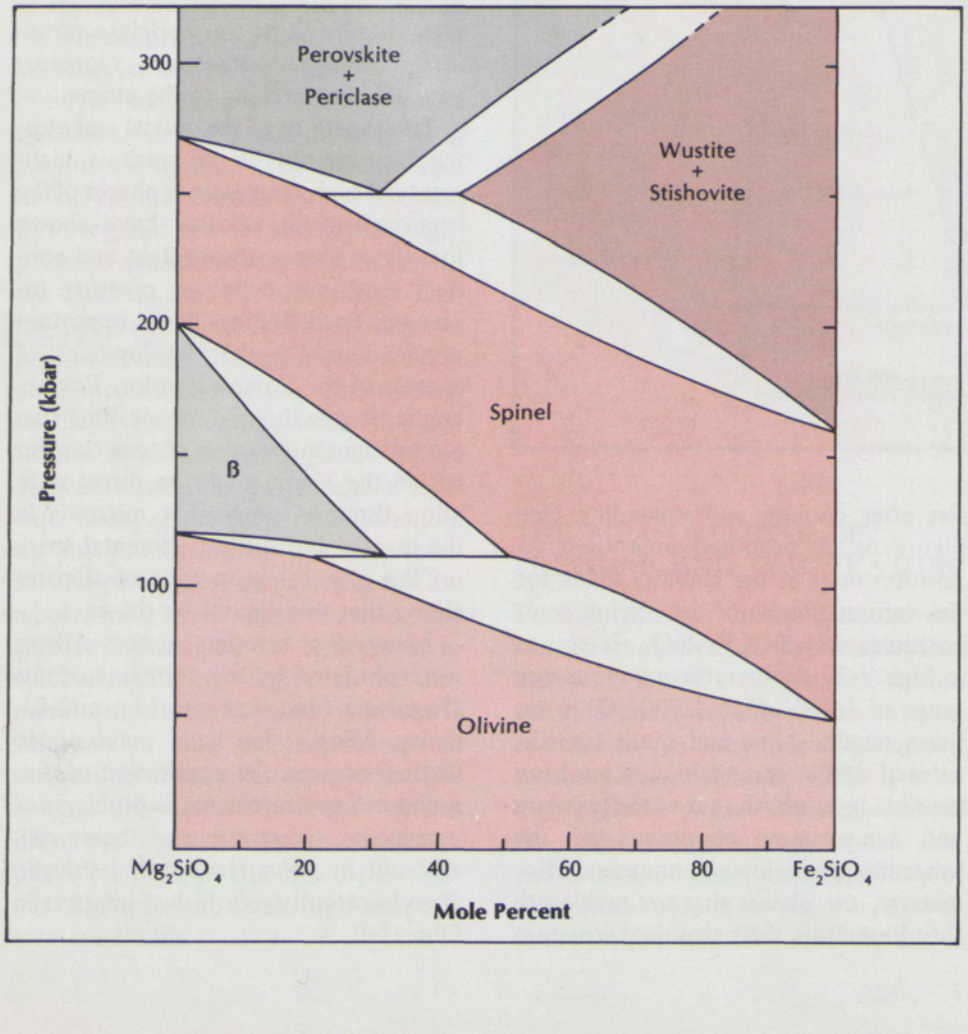


Figure 6. A sample wafer of Fe_2SiO_4 that has been subjected to pressure up to 250 kilobars at the center of the sample, and a temperature of 1,000°C. The sample has been removed for examination by microscopy and x-ray diffraction.

This micrograph shows a sample 0.3 millimeter from edge to edge. In the dark central highest-pressure region is a mixture of wustite (FeO) and stishovite (SiO_2); the ring outside of that is ringwoodite (Fe_2SiO_4 with the spinel structure), which is stable over a range of pressures approximately between 50 and 160 kilobars; and the outer portion is fayalite (Fe_2SiO_4 with the olivine structure), stable at pressures below 50 kilobars. Once formed, these high-pressure structures generally persist under ordinary surface conditions.

Figure 7. A proposed pressure-composition phase diagram for the olivine compound system Mg_2SiO_4-Fe_2SiO_4. This diagram is based on measurements in the diamond cell at 1,000°C to 1,500°C. Areas shown in white represent regions of mixed phases between the stability fields for phases shown in color.

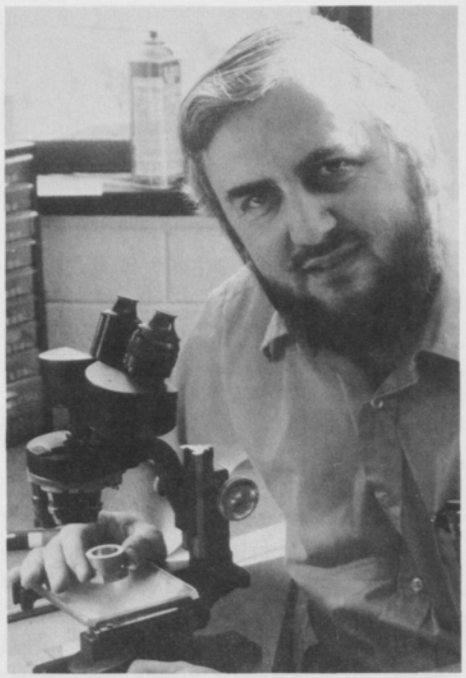
SYNCHROTRON X RAYS AND THE DIAMOND CELL

The plans for future research at Cornell in high-pressure mineralogy include the use of very intense x rays from the University's synchrotron to study transient high-pressure and high-temperature phenomena in the diamond cell. This will be made possible by the construction, now underway, of the Cornell High Energy Synchrotron Source, a national facility that will permit the tapping of x rays generated by

"We can observe, in the laboratory,
. . . minerals under the extreme conditions . . .
many kilometers below Earth's surface."

the new Cornell Electron Storage Ring. We expect the intensity of these x rays to be great enough to allow observation of the diffraction patterns of samples while the pressure and temperature are being changed. We should be able to observe kinetic effects in the phase transitions and to make studies of other phenomena that would be too short-lived to be examined by conventional techniques.

The great value of the diamond cell is that it allows us to make many kinds of measurements of Earth materials under conditions of geophysical interest. We can observe, in the laboratory, the state of minerals under the extreme conditions of pressure and temperature that exist many kilometers below Earth's surface. Each measurement provides information that cannot be obtained by direct observation; each new result provides another piece in the jigsaw-puzzle picture of Earth's interior.



Professor William A. Bassett, who joined the Cornell geological sciences faculty in 1978, received his B.A. degree in geology from Amherst College in 1954, and went on to graduate study at Columbia University. He received the M.A. in 1956, and the Ph.D. in 1959 with a dissertation on the origin of the mineral vermiculite. For three years after receiving his doctorate, he was a reseach associate in geochemistry at the Brookhaven National Laboratory, performing potassium-argon age-determination studies on a variety of rocks. In 1962 he joined the faculty of the Department of Geological Sciences at the University of Rochester, where he taught mineralogy and a field course on the geology of the western Adirondacks. He now offers these courses to students at Cornell.

The author of more than sixty articles on geology, Bassett is best known for his innovative work in applying high-pressure techniques to Earth materials, particularly with use of the diamond cell. He has also performed research in mass spectrometry, and is currently preparing to use Cornell's High Energy Synchrotron Source (CHESS) in high-pressure x-ray diffraction studies. These interests have led him to cooperate closely with members of the faculty in materials science and engineering.

In April of 1979, Bassett was elected a fellow of the American Geophysical Union. He is a fellow also of the Geological Society of America and the Mineral Society of America, and a member of the American Association for the Advancement of Science and the American Physical Society.

THE FLOW OF ROCK

by David L. Kohlstedt

Living on the surface of the Earth, we tend to assume that rocks deform only by brittle fracture. Most of the Earth's material, however, exists in the hot, highly pressurized depths of the planet, where minerals deform plastically in much the same way that metals such as lead and copper deform at room temperature.

The result is plastic flow of the mantle rock. Continents and seafloors move above the slowly convecting material. Motion in the mantle grinds out earthquakes along crustal faults. Mountains are thrust up, volcanoes emerge, and minerals from deep beneath the crust are deposited in midocean. None of these phenomena would occur if rocks deformed in a brittle manner under all conditions.

Understanding the plastic deformation of rock is the goal of research conducted by my group at Cornell. Results of our experiments promise to increase the scientific understanding of mechanisms within the Earth and may, some day, help people derive benefits from the planet's subsurface motion and avoid its hazards.

HIGH PRESSURE ON A LARGE SCALE

The temperature and pressure conditions of Earth's interior are difficult to duplicate in the laboratory, but they are the ones directly responsible for the mode of rock deformation in the mantle. At depths greater than 10 to 100 kilometers, temperatures are high enough to cause mineral grains to become soft, allowing plastic deformation and flow of the rocks. At the same time, high hydostatic pressure suppresses fracture.

In our laboratory work, we usually do not try to perform experiments at the pressures that exist at great depths. Mantle convection occurs to a depth of at least 400 kilometers, where the temperature is near 1,600°C and pressures are in excess of 100 kilobars (see Figure 1), but high-pressure equipment—such as the diamond-anvil cell—used for experiments in this pressure range do not lend themselves to deformation experiments in which stress and strain can be measured. Instead, we use high temperatures and confining pressures of

Figure 1

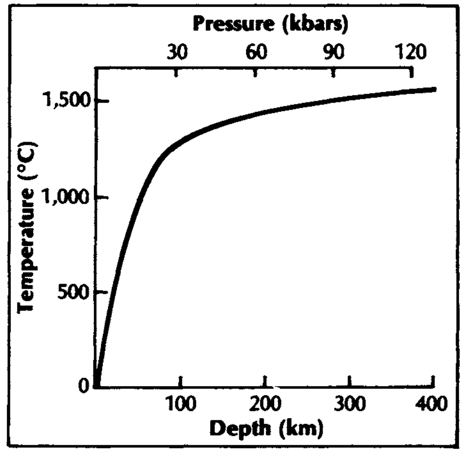


Figure 1. Temperature as a function of depth and pressure for the outer 400 kilometers of the Earth. Below 10 kilometers, the temperature is high enough so that rocks flow plastically while the high hydrostatic pressure prevents fracture.

only a few kbars to study creep in rocks and other ceramic materials.

In work of this sort, three types of confining or pressure media are used by various research groups around the world: solid, liquid, and gas. Solid confining media, usually soft materials such

Figure 2

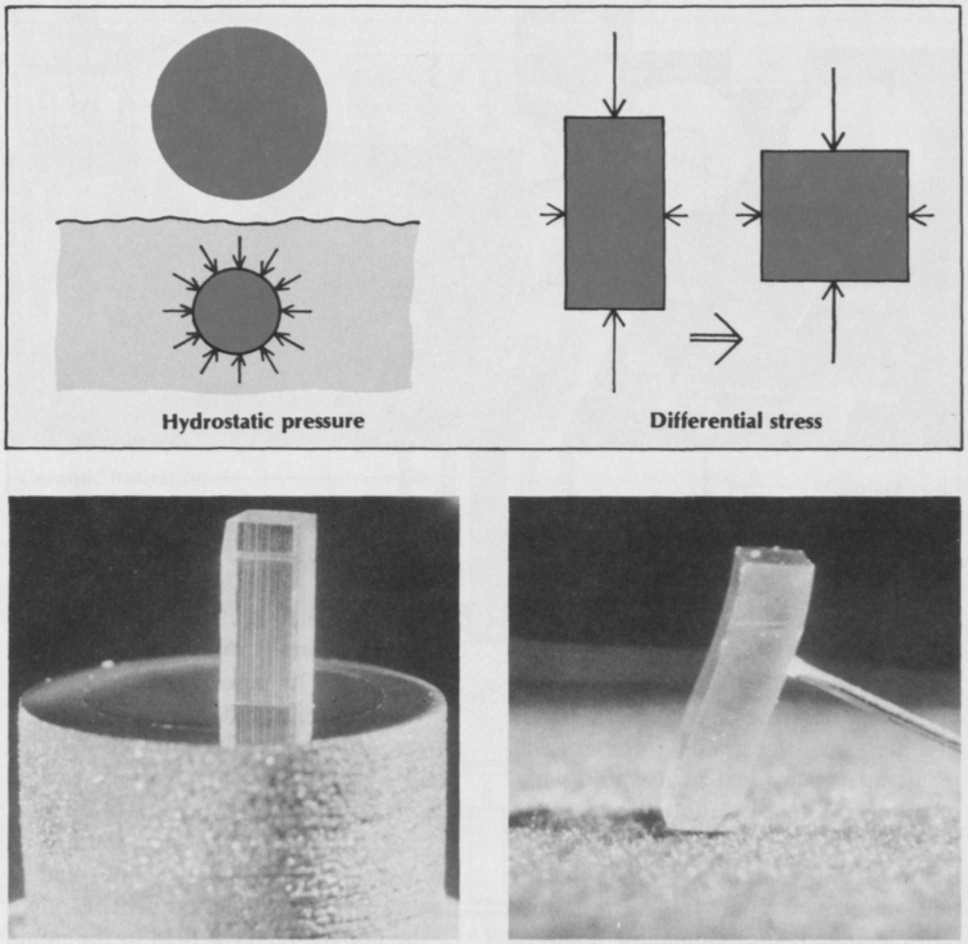


Figure 2. The distinction between hydrostatic pressure and differential stress. On the left, a balloon submerged in water is under a hydrostatic pressure; all three principal components of stress are equal. On the right, the rectangular box is subjected to a differential stress; the vertical principal stress component is larger than the horizontal principal stress component. Differential stresses, and not hydrostatic pressures, cause plastic flow in solids.

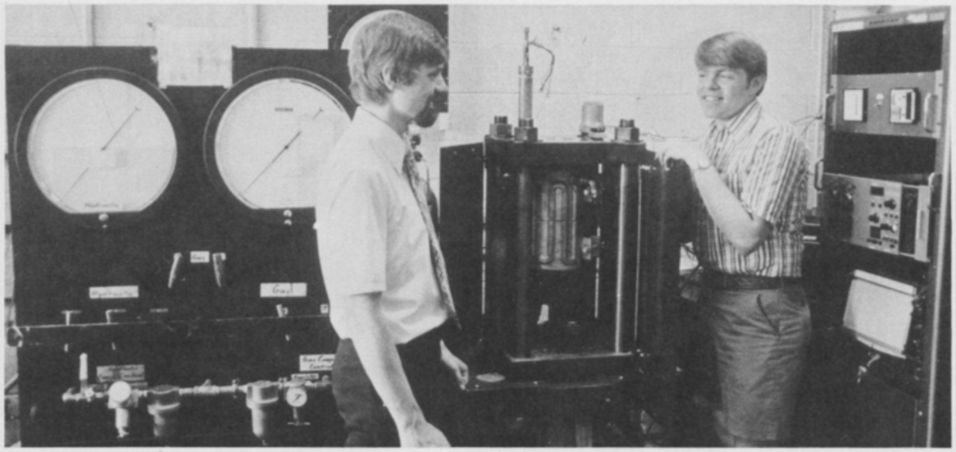
Left: "Before" and "after" photographs of a single olivine crystal show high-temperature deformation produced in the laboratory. The stress was applied vertically. The scale is shown by the piston head, about 1 centimeter in diameter, on which the undeformed sample rests.

as salt or lead, do not provide a purely hydrostatic stress field; they introduce differential or shear stresses that are often larger than those intentionally applied to deform the sample. Liquid media, such as oil or alcohol, eliminate the differential stresses, but their use is limited to temperatures below 400°C. In our experiments, the medium is a gas, usually argon. There are disadvantages in using a gaseous confining medium; liquids are easier to keep from leaking and higher pressures can be generated with solids. But like a liquid, gas provides a true hydrostatic pressure, and like a solid, it can be used to temperatures up to 1,400°C.

A simple experiment in which a geologic or ceramic material is heated and then cooled rapidly to room temperature demonstrates the importance of using a confining or hydrostatic pressure in studying the physical properties of rocks. During the heating and cooling cycle, the individual grains in the rock expand and contract, and because each grain is highly anisotropic in its thermal expansion, it exerts a force on neighboring grains. This force is usually sufficient to weaken the normal cohesion at the grain boundaries, so that after cooling the sample is easily disaggregated into its individual grains. A confining or hydrostatic pressure will hold the grains together, however, and prevent fractures from opening in the material.

In order to avoid fracture, the hydrostatic pressure on a sample generally must exceed the differential stress (which causes plastic flow). Differential stresses in the Earth (see Figure 2)

High-pressure apparatus is used for deformation experiments on minerals by Professor Kohlstedt (at left) and graduate student Reid Cooper, who holds the Corning Glass Works fellowship in materials science and engineering. At left is the gas high-pressure bench. At center is the pressure vessel (see Figure 3); the cylindrical assembly on top contains the furnace, and will be lowered for an experiment. The electronic controls are at right.



are believed to range between 10 and 1,000 bars, and we attempt to work in this range in our experiments. To apply stresses of this magnitude, the confining pressure must be in excess of 1 kbar, and is typically 3 to 4 kbars. In comparison with the diamond-anvil experiments performed by Professors Ruoff and Bassett (see articles in this issue), our work might more appropriately be called low-pressure research. Yet the experiments are by no means simple, partly because they involve much larger volumes and therefore much larger forces and energies than the diamond-anvil experiments.

THE CORNELL APPARATUS FOR DYNAMIC EXPERIMENTS

A sketch of a typical high-pressure apparatus used in dynamic experiments is shown in Figure 3. The construction is simple in principle. In practice, it challenges both the machinist and the metallurgist to produce a leak-free pressure vessel capable of withstanding the forces exerted by the gas.

Another important requirement is a jacket (see Figure 4) that can effectively isolate the sample from the surrounding gas, for if the gas were to penetrate into cracks in the sample, it could not act to close the cracks and inhibit fracture. A deformation experiment performed on an unjacketed polycrystalline ceramic or geologic material in a high-pressure gas environment will result in fracture just as it would without the high hydrostatic pressure. Several metals are used to jacket samples. Below 1,000°C, copper is an excellent choice: copper tubing is easily fabricated and, after annealing, is soft so that it readily flows into small scratches or pits on the sample surface when pressure is applied. At higher temperatures (copper melts at 1,083°C), nickel and iron are often used—and platinum may be chosen by research groups with large government grants.

Actually, all the materials that go into the hot zone near the furnace must be selected with care. Not only must they have low thermal conductivities to prevent excessive heat loss, but they must be chemically stable at the high experimental temperatures and in the presence of the other materials.

FILLING THE GAP FROM HOURS TO EONS

The high-temperature mechanical behavior of olivine, which composes approximately 75 percent of the Earth's upper mantle, is of particular concern to geophysicists. Convective flow in the mantle, which to a first approximation can be considered as the flow of olivine, is coupled to the large-scale motion of the overlying lithospheric plates and is manifested as continental drift. Models of the convective flow field in the mantle thus depend on our knowledge of the rheological behavior—specifically creep—of olivine. In the past ten years, several research groups have made laboratory measurements of the relationships among the macroscopic parameters: stress, strain rate, and temperature. More recently, investigators have begun to study the defect microstructure developed during creep experiments on olivine and olivine-rich rocks. Research has moved in this direction because of an important difference in time scale between the laboratory and the natural world.

Figure 3

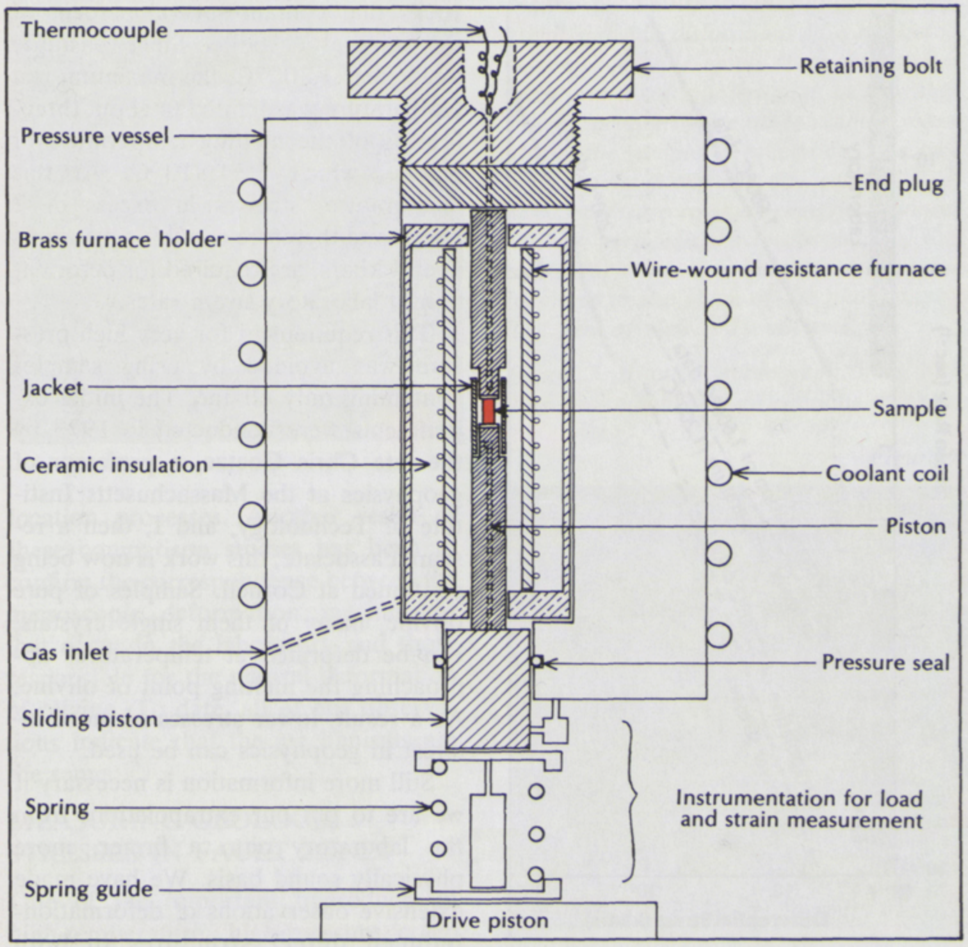


Figure 3. Schematic of a high-pressure apparatus used to study the physical properties of minerals at high temperatures in a confining gas medium.

The main element is a hollow steel cylinder that is heat-treated to maximize its strength. Gas is introduced through a small port and contained by a massive plug secured at the top of the cylinder. Six cone-shaped electrical feed-throughs sealed into this plug supply current to the furnace and allow the introduction of instruments such as a thermocouple. A tungsten or molybdenum piston enters the vessel through a dynamic seal in the bottom plug; it is used to apply deformation force to the sample. The sample is enclosed in a jacket that isolates it from the confining gas. The resistance-heated furnace, which is simply a thin-walled ceramic tube wound with wire similar to that used in toasters, is mounted at the center of a thin-walled brass can that fits snugly inside the pressure vessel. Because the temperature must be decreased from a maximum of 1,400°C at the furnace to less than 300°C at the inside wall of the pressure vessel, ceramic materials such as aluminum oxide or lavite are packed between the furnace tube and the brass can. To keep the pressure vessel below its softening temperature, cooling water is circulated through coils on the outside of the vessel.

Figure 4

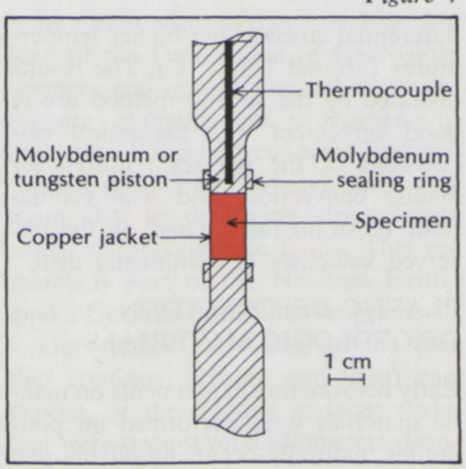


Figure 4. The piston-sample assembly. One important element of this assembly is the metal jacket that isolates the specimen from the high-pressure gas environment.

One of the major challenges to earth scientists is the extrapolation of laboratory data on creep obtained over a period of hours (10^{-4} years) to problems involving geologic times of millions of years (10^{+6} years). When dealing with deformation rates, this extrapolation must leap from minimum laboratory rates of 10^{-7} sec^{-1} to typical geologic rates of less than 10^{-12} sec^{-1}. In order to extrapolate confidently over so many orders of magnitude, we need to establish a correspondence between the mechanisms governing plastic flow

Figure 5

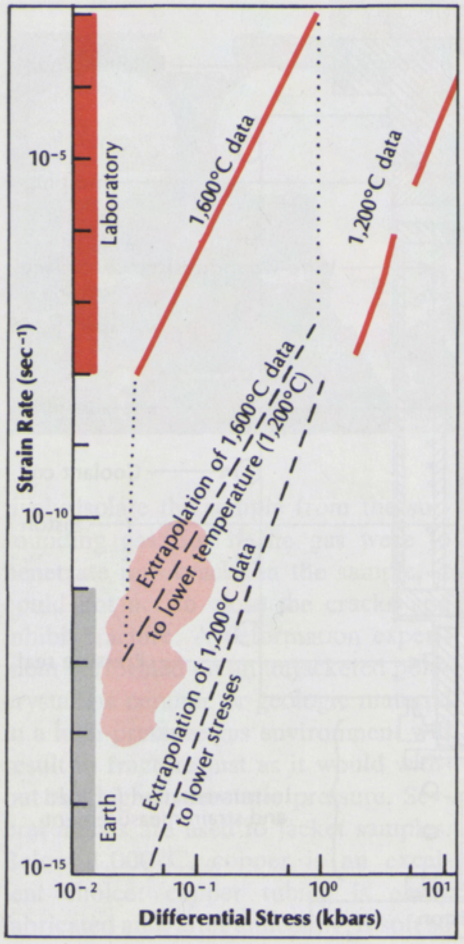


Figure 5. Extrapolation to geologic conditions of laboratory creep data for olivine-rich materials. Two commonly used approaches are extrapolation in stress and extrapolation in temperature. The latter method, which has been used extensively in the Cornell work, predicts deformation behavior for the mantle that is consistent with predictions based on geophysical observations (indicated by the shaded area).

in these diverse conditions. For this reason, there has been particular interest in understanding the relationship between the macroscopic conditions imposed in the laboratory and the dislocation microstructures observable in rock deformed both naturally and in the laboratory.

To obtain measurable deformation rates in experiments performed on the laboratory time scale, either the differential stress or the temperature must exceed that in the mantle. Since extrapolations in differential stress are generally less reliable than those in temperature, we have conducted experiments at geophysical stress levels, and relied on higher-than-natural temperatures to effect a measurable deformation.

Figure 5 shows a comparison of two ways of predicting the flow behavior of rocks in the Earth's upper mantle: laboratory data is extrapolated in stress and in temperature. It can be seen that for a given mantle strain rate, data obtained at a geologic temperature (about 1,200° C) but at higher stress levels predict a significantly higher flow stress than do the data generated at low differential stresses and higher temperatures (around 1,600° C). The results obtained by the second method are in good agreement with theoretical calculations of the stresses required for mantle convection, and with estimations of strain rates based on the observed velocities of continental drift.

PLASTIC DEFORMATION OF GEOLOGIC MATERIALS

Early deformation experiments on mantle materials were performed on peridotites, naturally-occurring olivine-rich rocks that contain several percent of the mineral enstatite. Since enstatite melts near 1,300°C, the maximum test temperature was limited to about three-fourths of the melting temperature of olivine, which is 1,810°C. At this temperature, stresses in excess of 2 kbars, and therefore confining pressures near 4 kbars, are required for deformation at laboratory strain rates.

This requirement for very high pressure was avoided by using samples containing only olivine. The initial experiments were conducted in 1973 by the late Chris Goetze, a professor of geophysics at the Massachusetts Institute of Technology, and I, then a research associate; this work is now being continued at Cornell. Samples of pure olivine, many of them single crystals, can be deformed at temperatures approaching the melting point of olivine. As a result, lower stresses of more interest in geophysics can be used.

Still more information is necessary if we are to put our extrapolations from the laboratory onto a firmer, more physically sound basis. We have made extensive observations of deformation-induced defect structures in both laboratory-treated specimens and naturally-deformed olivine. These observations provide detailed information on the motion and interactions of the defects responsible for plastic flow. In the upper mantle, deformation conditions are such that plastic flow proceeds by both glide and climb of dislocations within the individual olivine grains. Typical dislocation structures are shown in Figures 6 and 7.

The relation between stress and strain rate found in our experiments is exactly that predicted by theoretical models based on high-temperature dis-

Figure 6

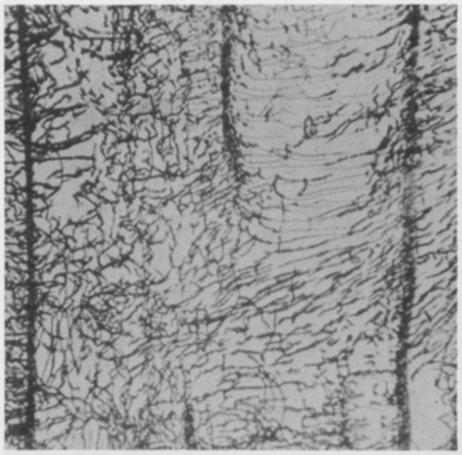
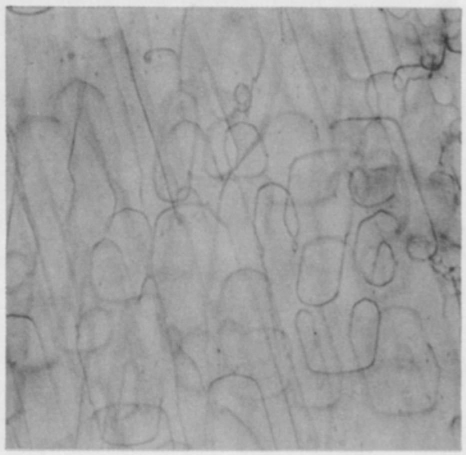


Figure 6. Transmission optical micrograph showing dislocations in a naturally deformed olivine grain (brought to the surface in a volcanic eruption in Hawaii). The dislocations were made visible by oxidizing the sample to precipitate iron oxide particles along the dislocations. The dark bands are rows of edge dislocations running perpendicular to the plane of the photograph; the fine lines are screw dislocations in the plane of the photograph. The field of view is 10 microns.

Figure 7. Another micrograph of an olivine grain, showing dislocations in their glide plane.

Figure 7



location processes. Another result of these comparison studies has been to confirm the correspondence between the microscopic deformation mechanisms that occur in the laboratory and those responsible for the natural deformation of olivine. To date, all of our observations indicate that the mechanisms are the same.

MEASURING GEOLOGIC STRESSES IN FAULT ZONES

One of the important byproducts of high-temperature, high-pressure creep experiments on rocks and minerals has been a technique for determining the stress levels at which rocks are deformed in the Earth. Using electron and optical transmission microscopy, we have analyzed samples that were plastically deformed at a known, constant differential stress, and have found a direct relationship between the magnitude of the stress and both the density of dislocations and the size of grains after deformation. These relationships give us a convenient, accurate method for determining the stress that deformed a natural rock sample.

In a joint effort initiated by John M. Bird of the Department of Geological Sciences and myself, Cornell researchers are applying the experimentally derived relations between stress and dislocation density and between stress and grain size to determine stress levels along ancient geologic faults. This research is part of the National Earthquake Hazards Reduction Program.

Our studies are based on the fact that continual erosion and uplift can expose, at the Earth's surface, rocks that were once several kilometers deep.

". . . we hope to gain a better understanding of . . . deformation at depth along the San Andreas."

Figure 8

Figure 8. Nordre Stromfjord shear zone, western Greenland. The lineations and banding developed as a result of plastic deformation of an initially homogeneous gneiss. Rocks 25 kilometers deep along the San Andreas fault may have a similar deformation-induced texture.

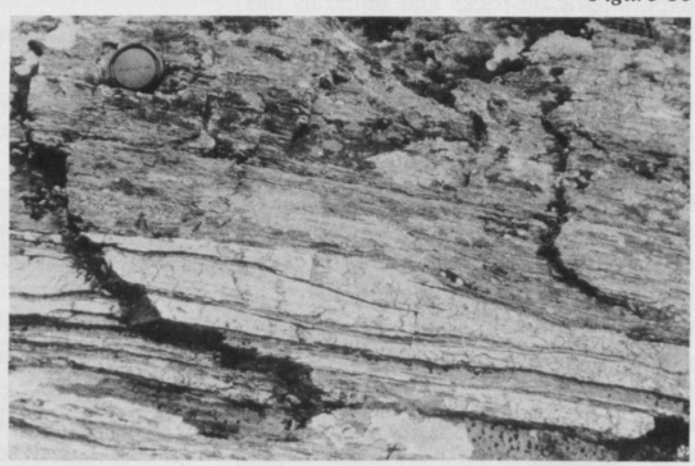
Figures 9 and 10. Plastically deformed rocks from deeply eroded shear zones.

Figure 9 shows a boudin in dike rock from a shear zone in western Greenland. Such boudins are formed during plastic deformation—in this case, at a depth of 25 kilometers and a temperature of 700° —and later are exposed by erosion. The scale is shown by the author's size 11 boots in the foreground.

Figure 10 shows Moine schists that were thrust over basal quartzite in the Moine thrust zone in Scotland. The textures, similar to those produced when steel is rolled into sheets, indicate that these rocks were deformed by extensive plastic flow. The scale is shown by the lens cap in the upper left area of the photograph.

Figure 9

Figure 10



In Greenland, for example, we are studying a shear zone that was 25 to 30 kilometers deep and at a temperature above 700° C at the time the rocks were plastically deformed. In Scotland we have collected quartz-bearing rocks from the Moine thrust fault zone that were 5 to 10 kilometers deep and near 500°C when the deformation occurred.

The highly lineated and banded rocks found in the Nordre Stromfjord shear zone in Greeland (Figure 8) developed during a period of intensive plastic deformation of initially homogeneous gneisses. The shear zone is about 10 kilometers wide and formed more than 1.6 billion years ago. The rock units bounding the shear zone were probably displaced by more than 100 kilometers. One model for this shear zone implies that it is an analog to the San Andreas fault in California; by studying the Nordre Stromfjord shear zone, we hope to gain a better understanding of the conditions and mechanisms of deformation at depth along the San Andreas.

In some regions of the shear zone, basic dikes were intruded and deformed during the large-scale shearing. (Professor Bird has suggested that the intrusion of the liquid dike material might have caused hydrofracturing of the country rock and that this hydrofracturing might function as a trigger for earthquakes in such regions.) Evidence for plastic flow of the dike and country rock is striking. A photograph (Figure 9) shows the stretching of a dark layer of intruded rock into boudins (sausage-shaped segments). The gneissic rocks have flowed smoothly around the boudins, indicating that these rocks were ductile at the time they were deformed.

Figure 11

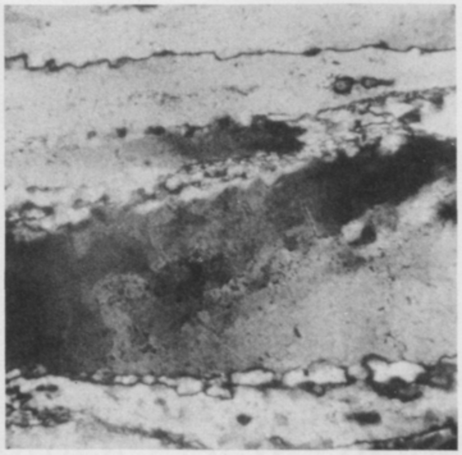
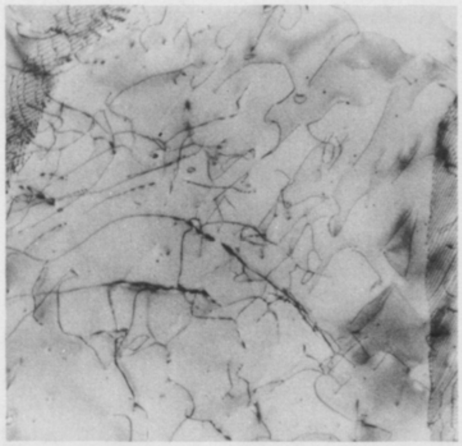


Figure 12



Figures 11 and 12. The calculation of deformation stress from micrographs of quartz grains. The samples were obtained in the Moine thrust zone in Scotland.

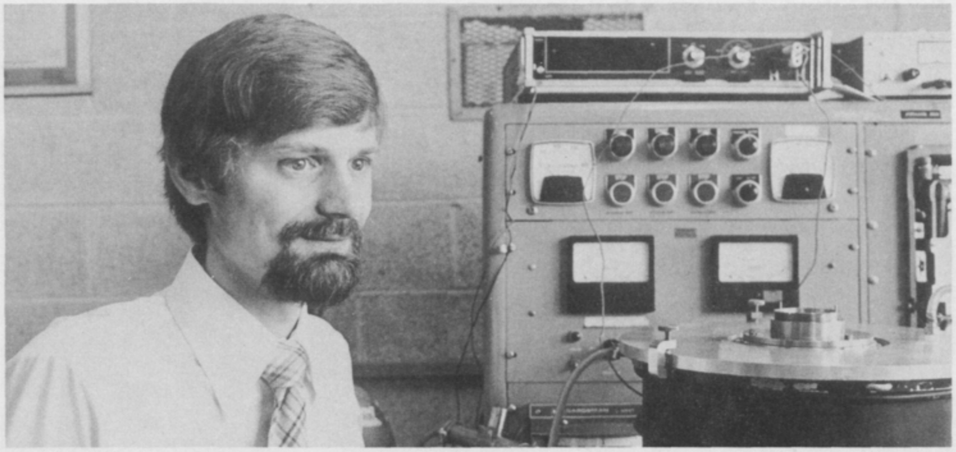
Figure 11 is a transmission optical micrograph. Serrations in the grain boundary (near the upper edge of the micrograph) have developed by migration of the boundary. With continued deformation, serrations pinch off to form new, small, recrystallized grains, as seen in the lower half of the micrograph. The size of these recrystallized grains indicates that the rocks were deformed at a differential stress of 1 kbar. The field of view is approximately 1 millimeter.

Figure 12 is a transmission electron micrograph of grain dislocations. The numerous curved dislocations and the well-developed dislocation boundaries indicate substantial high-temperature plastic deformation. In this case, a deformation stress near 1 kbar—in good agreement with results obtained from analysis of grain size—was calculated from the density of dislocations. The field of view is 5 microns.

Along the Moine thrust fault in Scotland, where Moine schists have been thrust over a quartz unit, the exposed rocks are severely plastically deformed (see Figure 10). The rocks at the contact have an appearance similar to that of steel rolled into a sheet.

Viewed in the optical microscope (Figure 11), the individual quartz grains are stretched out or elongated into ribbon-like grains: many of the grains have been plastically deformed to 5 to 10 times their original length. Since neighboring grains can migrate readily at elevated temperatures, the boundary between them becomes ragged during deformation, and eventually bulges or serrations pinch off to form new, small, recrystallized grains. The size of these grains, which is correlated to the stress level at which the rocks were deformed, indicates that deformation occurred under a 1-kbar differential stress.

The dislocation structure in these grains (see Figure 12) provides a second measure of the differential stress. This measure agrees well with the 1-kbar value determined from grain



size. In addition, the numerous curved dislocations and the well-organized dislocation boundaries seen in the micrograph are clear evidence that the deformation process was similar to the high-temperature, high-pressure plastic flow generated in laboratory experiments.

These findings are part of the evidence that knowledge of the physical processes in the Earth's interior requires study of earth materials at high temperatures and pressures, the salient features of the mantle. Such studies are important, for most of our planet lies beneath the accessible surface, and the mechanisms of heat transfer, mineral deformation, and material flow that predominate there control also the surface events and features that affect all Earth inhabitants. Knowledge of the processes that occur in the hot and stressful regions far below Earth's crust will contribute to secure and abundant life on this planet.

"... most of our planet lies beneath the accessible surface."

Assistant Professor David L. Kohlstedt teaches materials science and engineering and is also director of the electron microprobe facility of the University's Materials Science Center. Since coming to Cornell in 1975, Kohlstedt has conducted research on the deformation of ceramics, the behavior of ceramics and minerals under pressure, and applications of these studies to geologic materials.

Kohlstedt graduated summa cum laude from Valparaiso University in Indiana, and received master's and doctoral degrees in physics from the University of Illinois. In 1970-71 he held a postdoctoral fellowship at Cambridge University's Cavendish Laboratory, where he studied mechanical properties of high-temperature, high-strength solids. For four years before coming to Cornell, he was a research associate at the Massachusetts Institute of Technology, using high-resolution transmission electron microscopy to study defects in minerals, and continuing his study of the dynamics of Earth's interior.

Kohlstedt is a member of the American Association for the Advancement of Science, the American Ceramic Society, the American Geophysical Union, and the American Physical Society. At Cornell he is a member of the graduate faculties in both geological sciences and materials science and engineering; he has also served on thesis committees at universities in the United States and Europe.

COMMENTARY

An Interview with Cornell's New Engineering Dean

Soon after Thomas E. Everhart was chosen as Cornell's new dean of engineering last fall, we telephoned his office in Berkeley to ask for a photograph. "Oh, you're calling from Cornell," the secretary said. "Let me tell you: you are getting a really good man. We'll certainly miss him in this office." To his obvious professional qualifications for the deanship, we added the important one of success as a person. Not everyone can claim high recommendation by a secretary.

Since his arrival in January, Everhart has concentrated on becoming familiar with the College—its faculty, its departmental and administrative organization, its educational and research programs, its relations within and outside of the University. "If a dean is to represent a college, he must know it," he said. Others at the College are coming to know him as a soft-spoken man with a receptive mind but firm opinions, an administrator who bases his opinions on careful and accurate assessment, a dean whose outlook reflects a solid background in teaching and research, and a personable individual with exacting standards for himself and others.

Thomas E. Everhart became Cornell's seventh dean of engineering last January after twenty years of teaching and research at the University of California at Berkeley. He is a specialist in electron optics and electron physics and served as chairman of Berkeley's Department of Electrical Engineering and Computer Science. He holds the A.B. degree in physics (magna cum laude) from Harvard University, the M.Sc. in applied physics from the University of California at Los Angeles, and the Ph.D. in engineering from Cambridge University, England. He has held research appointments in England, Japan, and West Germany under Guggenheim and NSF fellowships, and has been active as an industrial consultant and in professional organizations. He is a fellow of the Institute of Electrical & Electronics Engineers.

As he was completing his third month as dean, he discussed with us some of his impressions and views on broad and specific topics, such as the state of the College, the aims of engineering education, and the role of technology in modern life.

The strength of any university lies in its faculty, Everhart said, and the Cornell engineering faculty is strong, creating a more dynamic environment for research and teaching than is found in most institutions. "The College is particularly strong in its young professors, a situation that augurs well for the future," he noted. "Obviously, the effectiveness of an academic program depends also on the quality of the students, which is excellent at Cornell; an additional characteristic that affects the nature of the College is that the student body is more heavily undergraduate—for largely historical reasons—than that of any other leading engineering school in the country."

Everhart's way of going about his study of the College has been to set aside one day a week for a visit to each school or department. At the time of our conversation, he still had three to go. Soon he plans to take a careful look at the various administrative functions of the College, and then the academic programs. (Later he hopes to reserve his special one day a week for his own research and professional activities. He would like to teach also, but in the immediate future, research has a higher priority because he feels that it is more difficult to keep up with developments in his rapidly changing research area of submicron structures than in an academic field.)

What has he found to be the special strengths of Cornell engineering research? Everhart cited the new submicron facility as an obvious example of the vigorous programs underway. In fact, the location here of the National Research and Resource Facility for Submicron Structures was a factor in his decision to come to Cornell. A longer-established facility that is also of great importance is the Materials Science Center, which provides equipment and research opportunities for Cornell investigators in a number of disciplines. Everhart has found active research in all the departments, and much that involves faculty members from two or more departments.

The effectiveness of the research programs demonstrates, among other things, the importance of good facilities, he said. "Cornell has been very successful in obtaining funding for equipment as well as for programs. At the present time, however, there are some building needs. The University is committed to providing additional housing, including clean laboratory space, for the submicron facility; another urgent need is more space for geological sciences."

In the long term, an important characteristic for a good engineering school is flexibility, Everhart said. In the hiring of professors, for example, a major consideration should be the ability of individuals to adapt to changes in specialty fields, in engineering and technology in general, and in society. Academic programs, too, must be adaptable in content and emphasis. "A school should attempt to provide fundamental instruction of lasting usefulness rather than to adjust its curriculum to meet the vicissitudes of the job market," he said. "Nevertheless, there are certain long-term trends that should be recognized. The use of computers, for example, is certain to become increasingly prevalent, and this is a development of importance not only to departments of computer science and electrical engineering, but to all engineering fields and to many of the liberal arts and sciences as well. Another obvious area of growth is electronics; for example, the integrated circuit industry, only twenty years old, is already a $10 billion-a-year business, and the figures are expected to double again within three to five years. This industry already hires many of Cornell's electrical

"This period of history is one of unprecedented challenge because of the extremely rapid rate of change"

engineering graduates and will soon want to employ more than half; the College must consider how to respond to this increasing need."

Although he has yet to make a close study of the College's educational programs, Everhart has formed some general opinions. The primary responsibility for curricula rests with the faculty, he noted, but everyone, including the dean, has the right to raise questions. Policies should be based on rational discourse and should represent enough of a consensus to receive the support of a strong majority, including that of the students, "who are, after all, the consumers in the educational enterprise." In fact, one recommendation Everhart has already made to academic heads is to institute a system of student evaluation of courses.

One educational need he perceives is a greater recognition by academic administrators that engineering is inherently an expensive branch of higher education. "Large lecture classes have much less of a place in engineering than in many areas of arts and sciences," he said. He cited a student-faculty ratio of about 12 to 1 as optimal at the undergraduate level in engineering. In particular, he pointed out, laboratory sections must be small because of limited expensive capital equipment which each student should learn to use. "This requires more teaching assistant help," he said. "Graduate teaching assistants have a valid role in providing instruction, and the experience is good for them. But they must be able to speak English clearly and understandably, and they must have thorough knowledge of the material they teach. Ideally they should also be interested in their students and be skillful teachers."

Engineering can and does provide a broad education, Everhart said, at least at a university where opportunity for study in many subject areas is available. Cultivation of the ability to think for oneself should be a major aim of education, he said, but this is not the exclusive province of any particular discipline or approach. Actually, the methodology and intellectual rigor characteristic of scientific and technological study provide a good educational base; many people who have become leaders or successful practitioners in nonengineering areas—lawyers and businessmen, for example—were educated as engineers. "While the two cultures described by C. P. Snow exist," Everhart said, "bridging the separation may be more effectively accomplished from the technical than from the liberal studies side: It is easier for scientists and engineers to learn about nontechnical aspects of life than for nonscientists to reach an understanding of problems and issues with a technical base. Public understanding of science and technology is essential in a democratic society, but although more 'popular' science is being written now than ever before, there is still much misunderstanding and sometimes, therefore, misapprehension. The recent concern about the safety of nuclear power technology illustrates the problem. Important issues are involved and there are legitimate concerns to be addressed, but most people do not have enough technical understanding to be able to make informed judgements."

Of course, the problems of democratic policy formulation extend to all

Everhart (at right), who is the Joseph Silbert Dean of Engineering, visited Silbert during a recent trip to Buffalo.

"Engineering can and does provide a broad education."

areas of life, he commented. For instance, the whole question of energy management, of which nuclear power is only one aspect, requires direction by the federal administration and rational decision making by leaders and citizens. "One of the difficulties at the present time is that many people fail to recognize that choices must be made," he said. "We cannot continue to use more oil if we cannot pay for it." He also pointed out, in this connection, that people of college age have much to contribute to the value judgements of society. "Students were right about Vietnam long before most of this country's older citizens," he said, "and many young people are advancing ideas about the energy issue that bear our careful and thoughtful consideration."

We asked Everhart about his views on the international aspects of American technology. "The United States has helped in the development of many nations that were technologically backward," he said, "and I have been a supporter of the aid programs. Many of these countries are now competitors; we should welcome this, but perhaps reevaluate the need for aid and reduce it when appropriate."

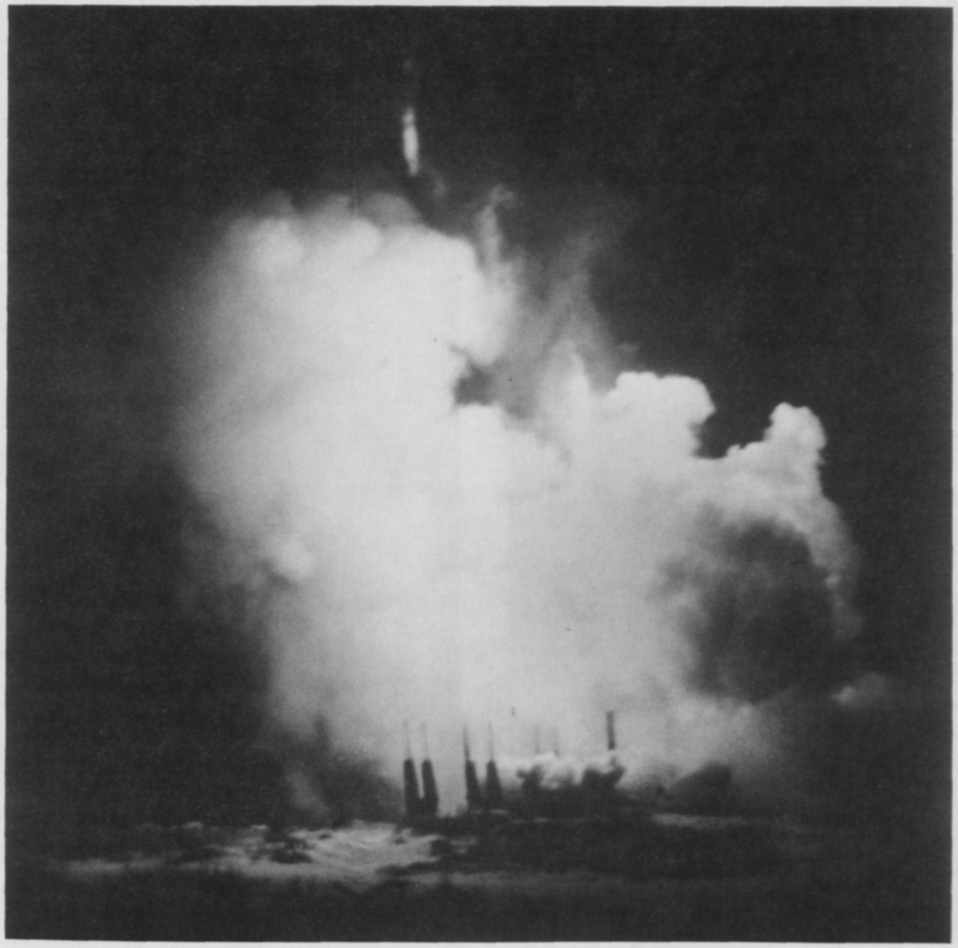
The consideration of issues and the advancement of opinions is an important aspect of university life, Everhart commented, and one that makes a university like Cornell vital and interesting. "Faculty members—and students and others of the university community—should feel free to speak out as individuals and citizens, on the basis of their special knowledge, though of course individual opinions must not be confused with institutional positions.

"This period of history is one of unprecedented challenge because of the extremely rapid rate of change," Everhart said. "Conditions in every area of life are changing so fast that people have difficulty adapting to them. But right now is one of the most exciting periods in all of human history. It's great to be alive now, and Cornell is an exciting place to be."—G.M.

VANTAGE

Cornell Group Conducts Rocket Experiment During Solar Eclipse

Six Cornell researchers were members of an American team that conducted rocket experiments in a remote area of Canada during last February's total eclipse of the sun. Led by electrical engineering professor Michael C. Kelley, the group obtained information about solar effects on Earth's electric field, part of a long-term study (see the October 1978 issue of this magazine). The Cornellians were among several hundred scientists who participated in the joint Canadian–United States Eclipse Program, in which thirty-five rockets were launched. Cornell's experiment was aboard one of eight sounding rockets launched and tracked by NASA from a temporary station near the Chukuni River in Ontario, on the path of totality of the eclipse.



Right: This gold-plated payload carried Cornell's equipment beyond the cloud cover to measure the ambient electric fields and plasma waves in the ionosphere. The payload also carried a Naval Research Laboratory experiment to measure density and temperature during the eclipse.

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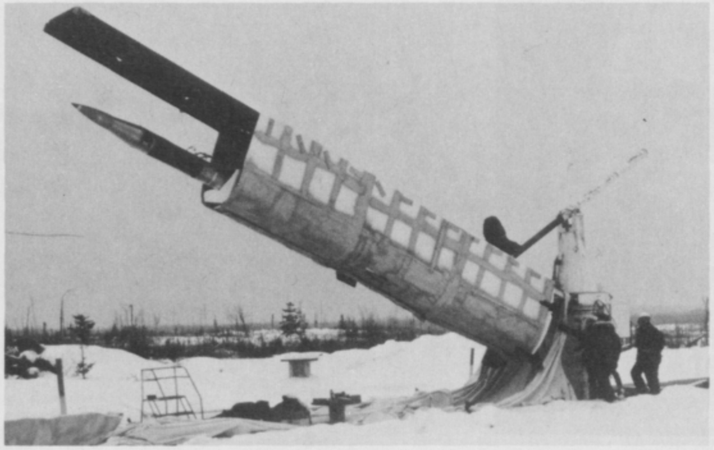

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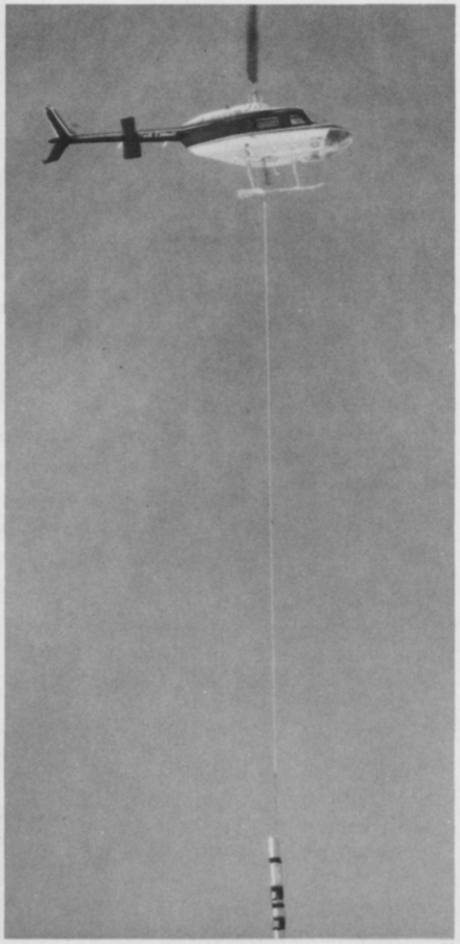

The payload carrying the Cornell instruments was elevated to a nearly vertical position for firing (1). After descent, a small airplane (2) was used to locate the payload in the forested area (3), blanketed by three feet of snow. The payload, still attached to the orange and white parachute (4), was recovered by helicopter (5) and unloaded back at the station (6). The recovery was made by a NASA crew who retrieved the payload from a treetop, secured it to the helicopter, and were picked up on a return flight. The pictures were taken by Mikki Parsons of the Cornell team.

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The Cornell group (7) included, left to right, Professor Kelley's nine-year-old son, Scott; Kelley; and graduate students Rob Pfaff and Miguel Larsen. The others were Paul Kintner, research associate; Steve Powell '82; and Mikki Parsons, administrative aide. Special warm clothing was provided by NASA; temperatures were as low as −40°F.

Equipment was assembled (8) in trailer huts brought in by NASA. Personnel were housed in motels in two nearby villages.

Not all the activity was scientific. The Cornellians found time to ski, snowshoe, and play "broom ball" with townspeople in the Red Lake arena (9).

Data is still being analyzed, Professor Kelley said, but the results look good. This was the last total eclipse observable from North America in this century.

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VANTAGE

The Art and Science of Blacksmithing

The anvil and forge may not be the latest in engineering equipment, but at Cornell this year some thirty freshman engineers took a short course in blacksmithing as part of their academic program.

The Art and Science of Blacksmithing, a six-week "mini-course" available to freshmen as part of their engineering orientation course requirement, is taught by Richard H. Lance, associate professor, acting chairman of the Department of Theoretical and Applied Mechanics, and associate dean of the College of Engineering. Each of the eighteen or so mini-courses offered every term is concerned with a subject of special interest to the professor who teaches it; The Art and Science of Blacksmithing represents an avocation Lance has developed over the past ten years, an interest that grew out of his professional concern with the theory of plasticity. The chief value of the course, he believes, is that it provides a good introduction to elementary engineering skills—although, of course, he "throws in" some instruction in metallurgy.

"Swinging a hammer gives one a feeling of actual heft and motion that complements the rigorous scientific treatment presented in a dynamics course," he explained. "And the experience of working with hot metal lends more meaning to an academic study of heat transfer. An engineer who appreciates the effort required to produce simple objects will have a more realistic understanding of how to form complex structures. Along with a knowledge of analytical techniques, a good designer needs a mechanical or electrical or thermal sense."

At the outset, the majority of students in the blacksmithing course showed little skill in hammering, Lance said. They had not developed the hand-eye coordination that is the most important requirement for the craft. In fact, a great many students entering engineering curricula today have little skill in manipulating things with their hands; they have not helped in carpentry projects as they were growing up, or tinkered with engines. Furthermore, it is possible for them to go all the way through a four-year degree program in engineering and never get their hands dirty. Lance feels that the education of an engineer should include instruction in basic manual skills, but that it should be provided by teachers who understand how these skills are related to the scientific basis of engineering. "Without the perception of a good instructor," he said, "a basic skills course would have very limited value."

The blacksmithing mini-course was offered for the first time this year, as an option in the Division of Basic Studies course 106, Engineering Perspectives. (Each freshman selects two mini-courses as part of the required work for 106.) Many of the students reported that they selected The Art and Science of Blacksmithing because they were intrigued by the prospect of learning an old skill still being practiced. One student wished to take the course partly because his grandfather had been a blacksmith in the Cornell area. All of them reported that the class was fun, although they discovered that blacksmithing, like most crafts, is harder than it looks. There were only a few minor burns, which served to point up the wisdom of the basic rule

Professor Lance uses the forge in Cornell's agricultural engineering building for class instruction in ironworking.

of the laboratory: Always assume that everything is hot unless you know for sure that it isn't.

The weekly laboratory sessions were held at the agricultural engineering building, where there is a coal-fired forge, one of the few on the Cornell campus. The students each fashioned two objects—a simple nail hook and a plant hanger. They learned how to bring the metal to red-hot temperature (1,500 to 1,600° F); how to judge the temperature of hot metal according to color; how to manipulate it by bending, twisting, drawing out, and hammering; how to quench it by immersion in water; and how to temper the metal, for reduced hardness and increased toughness, by reheating. In the weekly lectures, they learned something of the 3,500-year history of the craft of ironworking, and the fundamentals of the metallurgy of steel.

The old-time blacksmith, Lance explained, used high-purity wrought iron, which is rare today. Now the usual material is a low-carbon steel called *mild*. There have been few changes in technique or tools, however. Today, as always, the blacksmith uses a source of heat (the forge), an anvil on which to hammer the hot metal, tongs, and a set of hammers. The design of the anvil hasn't changed in four hundred years, and is very similar to the kind used in Roman times. One change is that in a contemporary forge, the air required to intensify the heat of the fire is usually supplied by an electric fan rather than a bellows. Another difference is that the hammers tend to be smaller. The old-fashioned blacksmith used hammers weighing up to twenty-five pounds, but the biggest one at Cornell, a one-man sledge, weighs only eight pounds. The reason is that the modern craftsmen forge small, generally decorative objects.

Lance's involvement in blacksmithing began when his wife, Ginny, bought an antique anvil for him at a farm auction. He set up a shop in an old chicken coop behind his home—a farmhouse, dating from the first half of the nineteenth century—and gradually acquired additional equipment, mostly at auctions. Now he has three

1

1. Dick Lance demonstrated blacksmithing skills on the Commons in downtown Ithaca during the city's annual festival this spring. Local crafts were one of the features of the three-day event.

"Along with a knowledge of analytical techniques, a good designer needs a mechanical or electrical or thermal sense."

forges, two anvils, including a very old one, and a variety of tools. He is thinking about building a new pole barn to house the equipment more satisfactorily, and to provide room for possible classes or demonstrations.

In addition to teaching his mini-course, Lance occasionally demonstrates blacksmithing skills at local fairs, such as the Brooktondale Apple Festival, the Dryden Field Days, the Etna Fair, and an annual craftsmen's day on the Commons in Ithaca. He finds much interest expressed by people of many occupations. In fact, he is thinking of organizing a regional blacksmith's circle, "rather like a sewing circle," which would bring individuals together for regular exchanges of information and display of objects they had made. In this part of upstate New York, rich in relics of the old days of blacksmithing, there are already a number of contemporary iron workers. These people include hobbyists as well as several professional farriers, who mainly fit manufactured horseshoes, but who also produce handwrought objects for home use and decoration.

Lance says he acquired his iron working skills partly by trial and error, and partly through expert instruction, which he recommends. He has attended two one-week workshops at Cooperstown, New York, where there is a model early-American village, complete with blacksmith shop and resident blacksmith. The workshops are limited to groups of eight; some of the students are hobbyists, and some are people who are seriously interested in developing a marketable skill.

Blacksmithing is one expression of an interest in early skills that both Dick and Ginny share. Ginny spins and weaves; an antique cherry loom looks at home in the living room of their old house. Dick has built a shaving horse—a device once used principally to make wood shingles—that he uses to fashion shuttles for the loom. Ginny's

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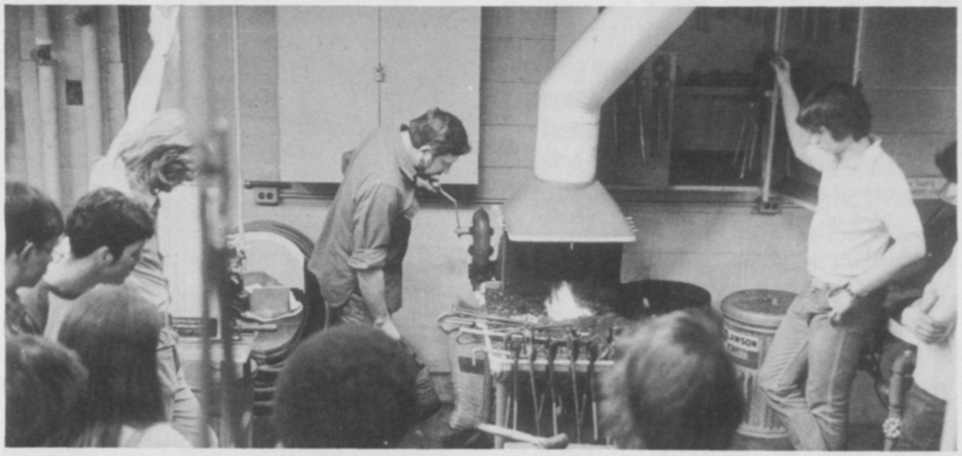

2. *Mrs. Lance shares her husband's interest in nineteenth century crafts. Here she weaves at her antique loom in the couple's home in Dryden, New York.*

3. *Techniques taught in Lance's mini-course on the art and science of blacksmithing included the control of air to produce the desired degree of heat in the forge.*

4. *The hot metal is shaped by hammering it on the anvil.*

5. *Lance demonstrates a spark test to determine the composition of steel. The course entailed an introduction to metallurgy as well as experience in using basic engineering skills.*

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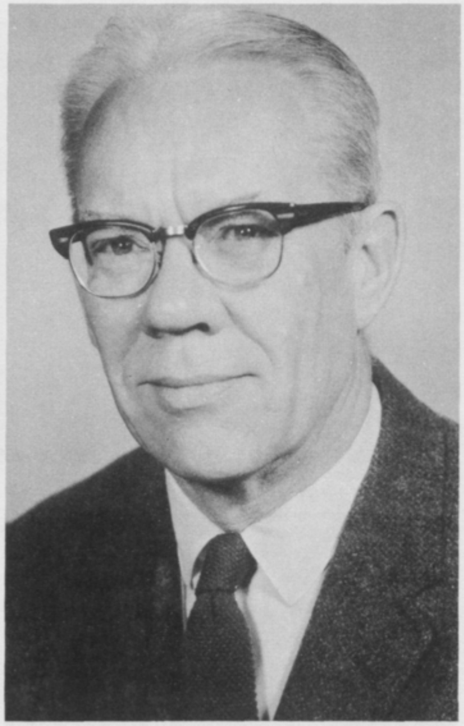
source of natural wool is Dick's flock of sheep.

Lance finds nothing incongruous about a personal affinity for nineteenth century ways and a professional engagement in contemporary science and engineering. Neither do his students in The Art and Science of Blacksmithing. They are discovering at an early point in their education that successful engineering today, as in the past, may benefit from the development of practical skills.—G.M.

REGISTER



Saunders

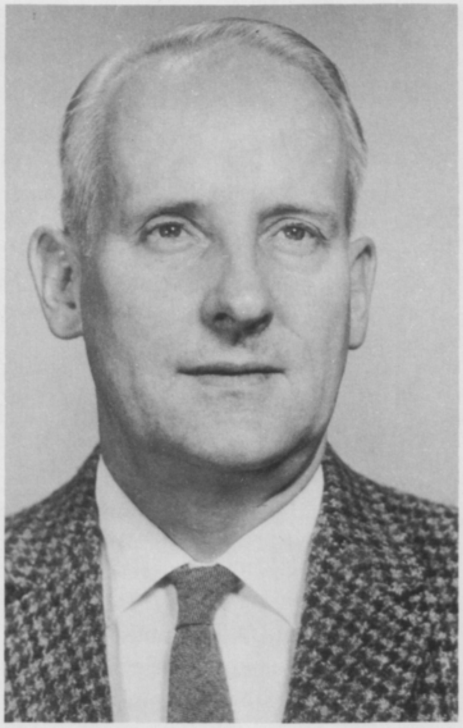
■ After thirty-two years at Cornell, Byron Saunders became professor, emeritus, of operations research and industrial engineering this summer. During his tenure here he served as head of his department and school, director of continuing education for the College of Engineering, and dean of the University faculty.

Saunders' most recent administrative post was as the elected dean of the faculty from 1974 to 1978, when he began a year's sabbatic leave. He came to Cornell as an assistant professor in 1947, achieved the rank of full professor in 1957, became head of the industrial engineering department in 1963, and served as the first director of the School of Industrial Engineering and Operations Research after this was formed in 1967. His term as director of continuing education was in 1971-74. In University affairs, his activities included participation in the Faculty Council, the Senate, and the Cornell University Council. In College affairs, he served for several terms each as chairman of the Policy Committee and as chairman of the Graduate Professional Programs Committee.

His early education was in electrical engineering; he earned the B.S. degree at the University of Rhode Island in 1937. Subsequently, he spent ten years with industrial firms engaged in the manufacture of radio and electrical equipment. During World War II he gave special lectures in electrical engineering at the Newark College of Engineering as part of the War Training Program in engineering, science, and management. In 1945 he received the M.S. degree in engineering economics from Stevens Institute of Technology. Throughout his career he has been active as a consultant to various industrial firms, including General Electric and Western Electric.

Saunders has been active for many years in professional organizations, particularly the American Institute of Industrial Engineers (AIIE), which elected him a fellow in 1975, and the American Society of Mechanical Engineers. These activities have included membership on national committees and a term as associate editor of the AIIE *Transactions*. He has also participated extensively in the accreditation functions of the Engineers' Council for Professional Development, a consortium of professional engineering societies, and is currently the AIIE representative. He is a member also of the American Association of University Professors, the American Association for the Advancement of Science, the Institute of Management Sciences, and the honorary society Alpha Pi Mu.

During his 1978-79 sabbatic leave, he travelled and worked on a book, and he plans to continue writing and working with professional society committees. He and his wife, Miriam, will maintain their home in Ithaca.



■ Arthur J. McNair, professor in geodetic and photogrammetric engineering and land surveying since 1949, became professor, emeritus, of civil and environmental engineering at the end of the 1978-79 academic year.

McNair received his professional education and did his first teaching at the University of Colorado, his home state. He received a B.S. degree with honors in civil engineering in 1934, and the M.S. in civil engineering and geology in 1935, and then was a member of the faculty until he came to Cornell. Among his contributions at Colorado was the introduction of instruction in photogrammetry and photo-mapping. His research in the 1940's on altimeters and mountains resulted in the addition of several 14,000-foot peaks to those known in the United States; he also discovered and named the two highest bodies of water in the country. In 1945 he received the degree of Civil Engineer from Colorado, and he is registered as a professional engineer and land surveyor in that state.

At Cornell McNair served as head of the Surveying Department until 1966, and has offered courses in photogrammetry, analytic triangulation, cartography, geodesy, surveying, and land surveying. At various times he conducted short courses in these and related subjects at other universities and research laboratories.

He spent a sabbatic leave in the early 1960's as a National Science Foundation science faculty fellow at the Institution for Geodesy in Sweden. In 1969-70 he spent a year as visiting professor at the University of Colorado, and initiated a statewide land-use and environmental-resources inventory carried out by photogrammetric methods. In 1977 he was a Fulbright scholar and visiting professor in geography at the University of New England in Australia.

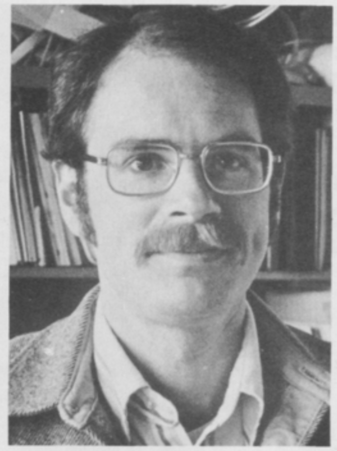
His recent research has been in such diverse areas as photogrammetric study of the human optic disc and nerve head, photogrammetric studies of bird flights, engineering analysis of satellite data for Southeast Asian agriculture, remote sensing techniques, and large-scale topographic and environmental mapping.

Throughout his Cornell tenure, McNair has served as a consultant to industrial firms and government agencies, including the National Aeronautics and Space Administration (NASA), the U.S. Geological Survey, the U.S. Army Engineers, and Amtrak.

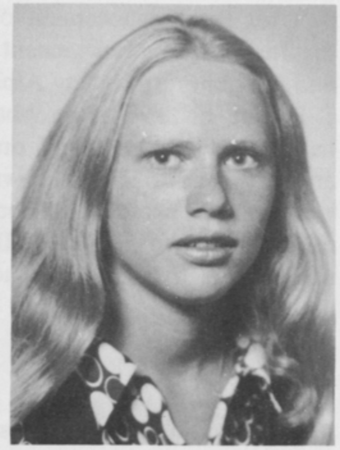
He has been active also in professional organizations, especially in committee or task-force work in his specialty fields. These organizations include the American Society of Civil Engineers; the American Society of Photogrammetry (ASP), which he served as president in 1961-62; the International Society of Photogrammetry; the American Congress on Surveying and Mapping (ACSM); and the American Society for Engineering Education. Among the honors he has received are a Presidential Award for Meritorious Service from ASP and a National Award for Excellence in Land Surveying from ACSM. He is a member also of Sigma Xi, Tau Beta Pi, and Chi Epsilon.

Ingraffea

Caughey



Haselbach



■ Two emeritus professors were honored by the American Concrete Institute this spring. S. C. Hollister, former director of the School of Civil Engineering and later dean of the College of Engineering for twenty-two years, received the Henry C. Turner Medal for notable achievements in the concrete industry. Cornell's Hollister Hall is named in his honor. George Winter, the Class of 1912 Professor of Engineering, emeritus, and former head of the Department of Structural Engineering, received the Joe W. Kelly Award for his educational contributions.

■ This year's recipient of the Excellence in Engineering Teaching Award is Anthony R. Ingraffea, assistant professor in the Department of Structural Engineering. The $1,000 award is sponsored by the Cornell Society of Engineers and Tau Beta Pi. Last year Ingraffea received the Professor of the Year Award from Chi Epsilon, student honorary society in civil engineering. A specialist in fracture mechanics, he received his doctorate from the University of Colorado in 1977 and joined the Cornell faculty that fall.

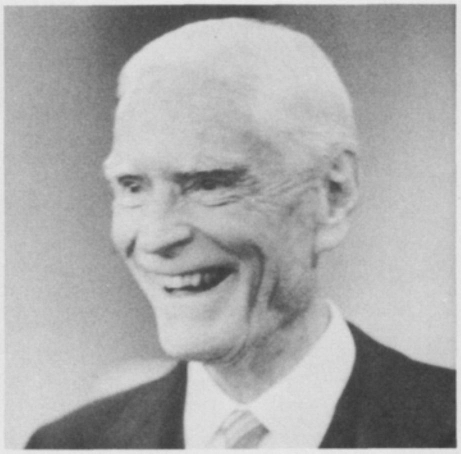
■ A former recipient of the engineering teaching award, David A. Caughey, recently received the Lawrence Sperry Award of the American Institute of Aeronautics and Astronautics for outstanding research by a scientist under thirty-five. The work was in developing computer codes that are now being used in aircraft design. Caughey, an assistant professor, earned a Ph.D. from Princeton University in 1969, served as an NSF exchange scientist in the U.S.S.R., and worked in industry before coming to Cornell in 1974.

■ Graduating senior Liv Haselbach was this year's recipient of the Fuertes Undergraduate Medal for scholastic achievement, awarded by the School of Civil and Environmental Engineering. Although the medal has been awarded since 1895, this year's award marks a number of firsts. Liv is the first woman to receive the medal, the School's first Coop student to be at the top of the class, and the first award recipient to graduate in fewer than eight terms. She plans to enter the Ph.D. program in chemical engineering at Berkeley.

■ For a senior project in aerodynamics, a group of mechanical engineers succeeded in computer-designing and assembling two high-speed bicycles this spring, although an attempt at the world speed record for man-powered vehicles was cancelled when weather delayed testing. The group (left to right at left, David Kerner, Martin Fisher, Daryl Robbins, and David Wilson) worked with Professor Albert George. Airfoils and extremely high gear ratios were among the modifications that permitted speeds near fifty mph.

■ Warren Smith, who graduated this June in mechanical engineering, was this year's co-captain of Cornell's gymnastics team. He is pictured in a dismount from the high bar during a meet with Army this season. His performances helped bring the team's best season in five years. Warren started his career as a floor exercise performer, but became Cornell's best competitor in three events and second in two others. The floor exercise is still his favorite, he says, because "A part of you goes into the moves you make and the routine you pick. No two performers display the same moves." Warren worked as a Coop student for the Nordson Corporation. He hopes to continue his gymnastics training after he enters the working world.

Ward



■ Funding for the J. Carlton Ward Jr. Professorship of Nuclear Energy Engineering has been completed with a gift to Cornell of $865,000 from a leading industrialist in whose honor the new chair is named.

Ward is a 1914 mechanical engineering alumnus of Cornell, a former member of the University's Board of Trustees, a member of the Cornell University Council, and an emeritus member of the Engineering College Council. At the age of eighty-six, he still travels to Ithaca from his home in Connecticut to attend meetings of the engineering council. He contributed to the design and establishment of the J. Carlton Ward Jr. Laboratory of Nuclear Engineering, which opened here in 1961.

Ward's purpose in establishing the new professorship is to provide a nucleus for a Cornell program in energy research and development. It is hoped that the appointment will serve to promote the collaboration of faculty members from many disciplines, such as biological sciences, chemistry, physics, economics, agriculture, and law, in seeking long-range solutions to civilization's complex energy problems.

Ward is a former director of Pratt and Whitney Aircraft Corporation (now United Technologies), and before his retirement in 1961 was president and chairman of the board of Vitro Corporation. During his career he also served as vice president and general manager of Pratt and Whitney; president and chairman of the board of the Fairchild Engine and Airplane Corporation; and chairman of Thompson Industries, Inc.

■ Grants totalling more than $1.3 million in support of the College's research and teaching programs have been awarded or pledged in recent months by industrial organizations.

An Award of Excellence, amounting to $500,000 over a five-year period, was given by the Atlantic Richfield Foundation. The award, which is the foundation's major educational grant, is made annually to a few universities. The Cornell funds are to be used at the discretion of the College of Engineering.

From the Emerson Electric Company, the College received $125,000 as its share of a total gift to Cornell of $300,000. The grant will be used to renovate and reequip the materials and metal-cutting laboratory in the Sibley School of Mechanical and Aerospace Engineering.

The Standard Oil Company of California more than doubled its previous level of support, pledging $250,000 over a five-year period. The money will provide continuing support for chemical engineering in the form of a graduate fellowship, a research grant, and unrestricted funds. Additional funds will help develop the kinetics and catalysis laboratory, support the M. Eng. (Chemical) degree program, and provide scholarship aid for mechanical engineering undergraduates.

As part of a total commitment to Cornell of $325,000 over a five-year period, companies affiliated with the Mobil Oil Corporation have pledged about $48,000 a year for engineering programs. Included are grants from the Mobil Foundation for the School of Chemical Engineering, the Minority Engineering Program, and unrestricted funds. In addition, the Mobil Research and Development Corporation has pledged $15,000 a year as a sponsor of the Cornell Program for the Study of the Continents (COPSTOC), conducted by the Department of Geological Sciences.

The Hewlett-Packard Company has donated or pledged equipment valued at more than $130,000 for the School of Electrical Engineering. The equipment includes a HP1000/45 computer.

Contributions of $50,000 each have been designated by the Inland Steel Company and the Garrett Corporation. The Inland gift is financing improvements in the George Winter Laboratory, a large-scale testing facility for research in structural steel. The Garrett gift is unrestricted.

■ Several groups from the People's Republic of China visited Cornell this year.

1. Possibilities for a student exchange were discussed by Cornell President Frank H. T. Rhodes (at center), Cornell electrical engineering Professor Walter H. Ku, (at right), and delegates from the Chinese embassy in Washington, D.C.

2. A delegation of Chinese geophysicists visited the Cornell Department of Geological Sciences in November, as part of a tour of several United States universities and petroleum industries. Here Cornell Professor Bryan L. Isacks discusses Cornell research in seismology. Department chairman Jack E. Oliver (at rear) briefed the visitors on the COCORP program, which uses seismic exploration techniques to explore deep strata in the Earth's crust.

3. Dr. Chin Tru-jung (left), leader of the Chinese geophysical delegation, speaks with Professor Oliver through his interpreter (at right). Also present was Professor John Kuo of Columbia University, who accompanied the delegation.

4. Professor Robert Kay (at left) explains the research significance of crustal xenoliths—samples of the deep Earth's crust brought to the surface naturally. The possibility of obtaining xenoliths from China for Cornell's collection was discussed.

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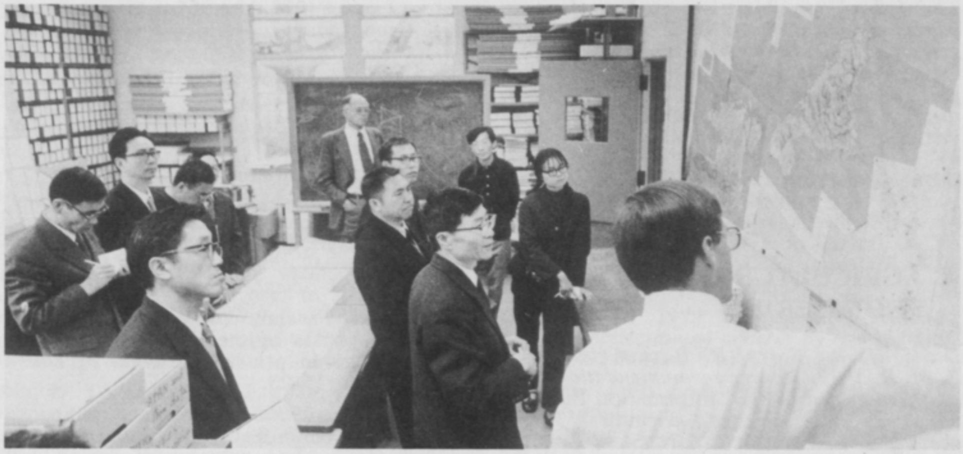

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FACULTY PUBLICATIONS

The following publications and conference papers by faculty and staff members and graduate students of the Cornell University College of Engineering were published or presented during the period December 1978 through February 1979. Earlier entries not included in previous listings are indicated by a date in parentheses. The names of Cornell personnel are in italics.

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Clancy, P.; Gubbins, K. E.; and Gray, C. G. (1978). Thermodynamics of Polar Liquid Mixtures. Paper read at Faraday Discussion 66, 13–15 September 1978, at University of Kent, Canterbury, England.

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