ENGINEERING

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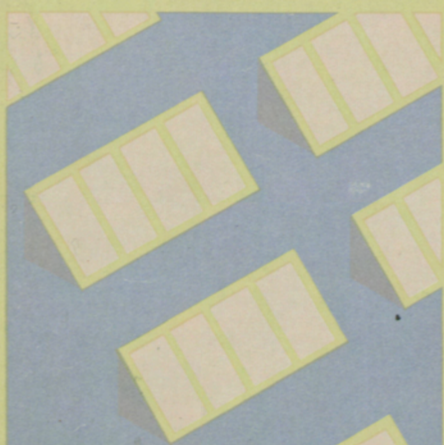

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PLANNING FOR ENERGY R AND D

IN THIS ISSUE

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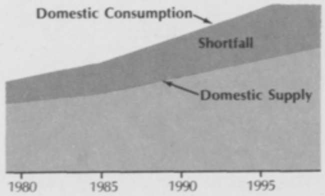
Opposite: Coal-fueled Milliken Station on Cayuga Lake north of Ithaca and Cornell University is to be augmented by a new coal-fueled generating station. An earlier plan to build a nuclear-powered facility was successfully opposed by area environmentalists who were concerned about the effects of thermal discharge into the lake. Outside front cover: Energy sources important for future supply include coal, nuclear energy, solar energy, and petroleum.



TOWARD A NATIONAL PROGRAM FOR ENERGY RESEARCH AND DEVELOPMENT

A Report on the Cornell Workshops

During the winter of 1969-70, the United States experienced its first actual shortages of energy. The time had come for warnings and predictions of an impending crisis to begin to materialize.

By the spring of 1973 it had become clear that the overall problem was not going to get solved by trusting to the laws of economics and the initiative of industry. The issues were too complex; the technological development required for various possible energy supply systems too expensive, uncertain, or time-consuming; the need too urgent. Circumstances new in the American experience were involved: limits to readily available resources, and concern about environmental consequences of various kinds of exploitation and development.

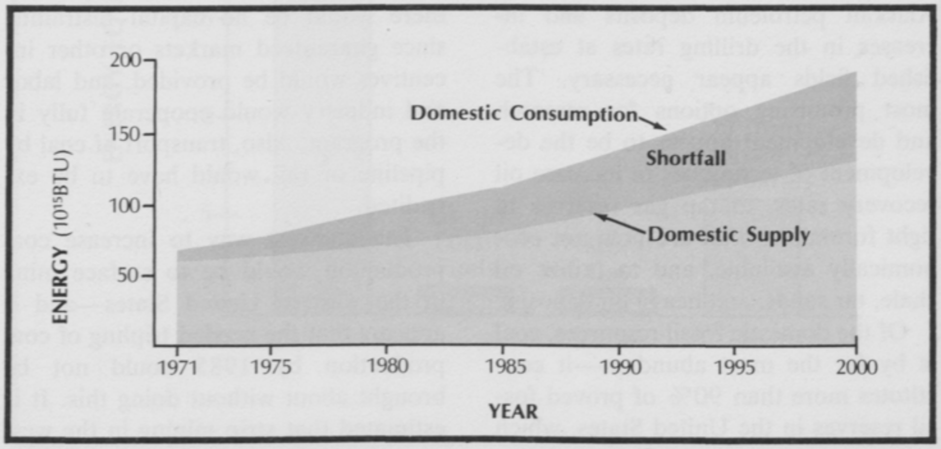
Clearly, there was a need for unprecedented national planning, policy development, and implementation that would be concerned with long-range as well as immediate measures and would involve government, industry, and the universities. The President called for a research and development program in energy to be funded at $10 billion over the next five years, and as a first step, the chairman of the Atomic Energy Commission (AEC) was directed to prepare a comprehensive plan for such a program.

It was here that Cornell provided direct assistance. At the invitation of the AEC, the University organized and conducted the Cornell Workshops on the Major Issues of a National Energy Research and Development Program, which brought together some eighty leading authorities from government, industry, and the academic community to examine the present situation, assess priorities, discuss alternatives, and formulate recommendations.

Participants in each of four panels were assisted by representatives of industry and governmental agencies who served as "briefers" in their special areas of knowledge and expertise. These Workshops, held in September and October, 1973, in Washington, have afforded the AEC a comprehensive basis for formulating its plan.

A summary report of the Workshops, very briefly reviewed here, may be obtained from the AEC Technical Information Center, P.O. Box 62, Oak Ridge, Tennessee 37830, as report TID-26528. Some 3,500 copies of the Report have been distributed so far, and another edition will be published by the Government Printing Office.

Largely responsible for the Cornell Workshops are two College of Engineering faculty members. Peter L. Auer, professor of mechanical and aerospace engineering and director of the Laboratory of Plasma Studies, conceived and initiated the effort and prepared an overview statement for the summary report. Simpson Linke, professor of electrical engineering, organized and coordinated the Workshops and was responsible for the preparation of the report. Another active participant from Cornell was Hans A. Bethe, the John Wendell Anderson Professor of Physics and Nobel laureate, who served as chairman of the Workshop on Advanced Nuclear Power. Edmund T. Cranch, dean of the College of Engineering, and Robert L. Von Berg, professor of chemical engineering, also participated in several of the Workshop sessions.



Projected energy shortfall in the United States, as an indication of the need for R and D efforts. These data, adapted from the Cornell Report, are based on a December 1972 forecast of the Department of the Interior. The forecast assumed no major changes in current production and consumption patterns. Domestic supply includes natural gas, petroleum, coal, hydroelectric energy, and nuclear energy. The shortfall is presumably to be met by imports or rationing. This information was considered in the Cornell Report to give a reasonable feeling for the magnitude of the energy problem.

THE NECESSITIES: ENERGY SOURCES AND A PLAN

From the outset of the Cornell Workshops, it was apparent that a national energy program must encompass both short-term strategy and long-range planning. The outline of a timetable for the R and D was clearly needed, as well as overall policy to guide the formation of specific plans by public and private organizations.

Accordingly, panels were formed to consider the fossil fuel option, the short-term nuclear option, advanced nuclear power, and institutional patterns in energy research and development. Matters of safety and environmental protection were to be considered at all points.

The central facts concerning energy supply that emerged from the Workshops are: (1) We must rely on fossil fuels, notably coal, to tide us over until nonexpendable energy sources can be adequately developed. (2) We must rely on nuclear energy in the longer term, since only this appears to be available soon enough to replace fossil fuels as they are depleted. (3) The orderly investigation of long-range alternatives such as advanced breeder reactors, fusion reactors (which have not yet even been demonstrated as feasible), or the utilization of solar or geothermal energy should be started, since considerable time will be required to develop and implement them.

Timing was shown to be a crucial factor in all these developments. For fission reactors, for example, it is necessary to plan carefully so that fission-able material is not consumed faster than it can be supplied. Long-range options must be developed in time to make them ready to take over when needed. A consensus was that the allocation of tasks and responsibilities must be decided upon, and economic support or incentive provided as necessary. Furthermore, it was felt that overall policy must be set forth so that all sectors, public and private, can deduce their roles and make coherent plans.

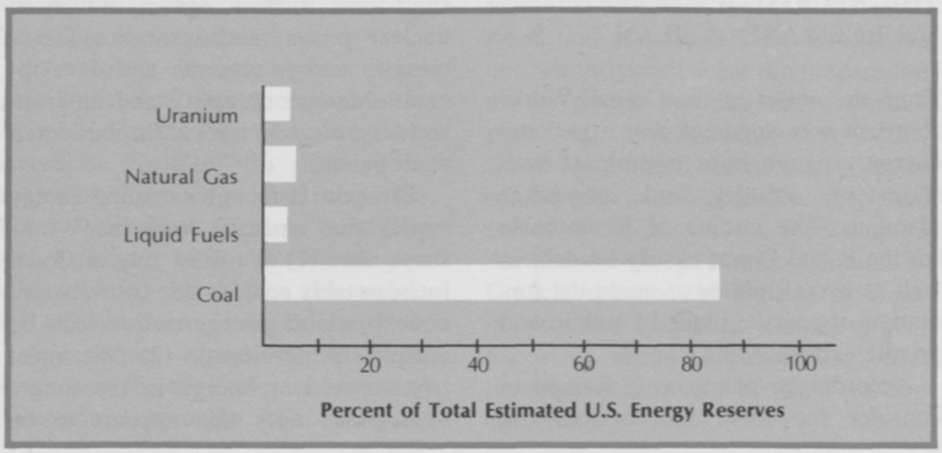
THE PANEL ON THE FOSSIL FUEL OPTION

A continued dependence on conventional fossil fuels—coal, oil, and gas—was seen by the panel as inescapable for the United States for the next twenty or thirty years. The time required for developing alternative energy sources, combined with an increasing demand (even with conservation efforts), means that the nation must rely on increased exploitation of gas and oil reserves and increased mining of coal, especially if national self-sufficiency in energy supply is to be achieved.

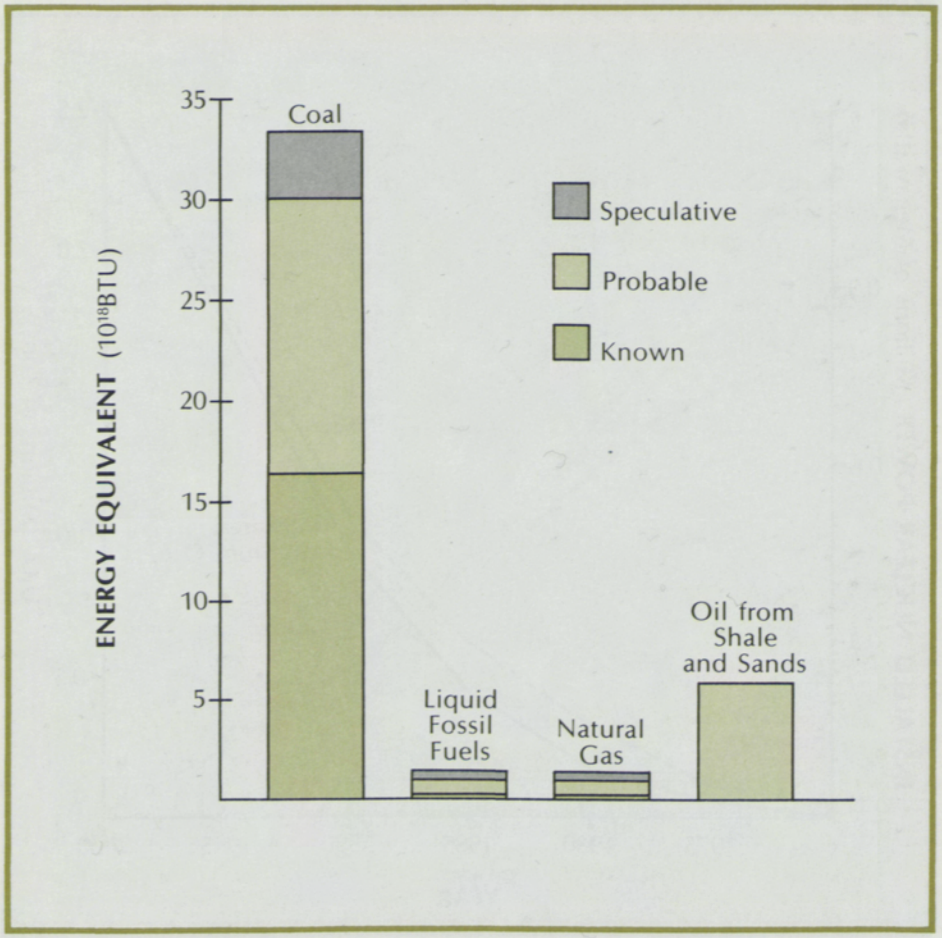
Although domestic liquid oil and natural gas production could be increased in several ways, the most optimistic estimates by the National Petroleum Council project a 40% increase for oil and a 38% increase for gas, and the most pessimistic show no increase or a decline. It is considered unlikely that production rates could be substantially increased on the basis of new discoveries, and that even the maintenance of present rates will require further economic incentives and accelerated leasing of on-shore and off-shore federal holdings. Use of the Alaskan petroleum deposits and increases in the drilling rates at established fields appear necessary. The most promising options for research and development appear to be the development of techniques to increase oil recovery rates, to tap gas reserves in tight formations that are now not economically available, and to utilize oil shale, tar sands, and heavy oil deposits.

Of the domestic fossil resources, coal is by far the most abundant—it constitutes more than 90% of proved fossil reserves in the United States, which is estimated to have close to one-half of the world's total coal resources. Projections based on assessments of how much increase can be made in the production of gas and oil, and on the assumption that imports can be maintained at 1970 levels, show that 1.8 to 2.1 billion tons of coal will be needed annually by 1985. The present level is 0.6 billion tons. In estimating whether such an increase is possible, the panel made the assumptions that environmental constraints would be relaxed, there would be no coal resource constraints as a result of federal leasing policies, there would be no capital restraints, since guaranteed markets or other incentives would be provided, and labor and industry would cooperate fully in the program. Also, transport of coal by pipeline or rail would have to be expedited.

The quickest way to increase coal production would be to surface mine in the western United States—and it appears that the needed tripling of coal production by 1985 could not be brought about without doing this. It is estimated that strip mining in the west



Estimations of major proved energy reserves in the United States. These are considered to be materials in known deposits available for recovery under existing economic and technological conditions. Comparisons are made on the basis of energy equivalence in Btu; the total energy from the various proved reserves amounts to 4,885 x 10^{15} Btu. The figures for coal represent deposits in seams at least 42 inches thick at less than 1,000 feet overburden; liquid fuels are proved reserves of oil and natural gas liquids; the estimate for uranium is calculated for light-water reactor usage at 400 x 10^{9} Btu per short ton of reasonably assured U_3O_8 costing less than \$15 per pound.



Estimates of recoverable fossil fuel resources in the United States. Coal is estimated at 50% recovery; the total corresponds to 1,605 billion short tons. Liquid fossil fuels include gas liquids (estimated at 82% recovery) and crude oil (42% recovery); the total corresponds to 289 billion barrels. Natural gas is estimated at 82% recovery; the total corresponds to 1,413 trillion cubic feet. Potentially recoverable oil from shale and tar sands has been estimated at one trillion barrels. The data, gathered from various sources, are cited in the Cornell Report.

could provide close to one billion tons per year by 1985. Eastern coal is mostly underground and the lead time for getting production underway is considerably greater than for strip mining. Also, extensive improvements in technology and health and safety provisions will be required before production can be expanded significantly. Estimates are, however, that an annual level of 0.8 billion tons of coal from eastern mines could be achieved by 1985.

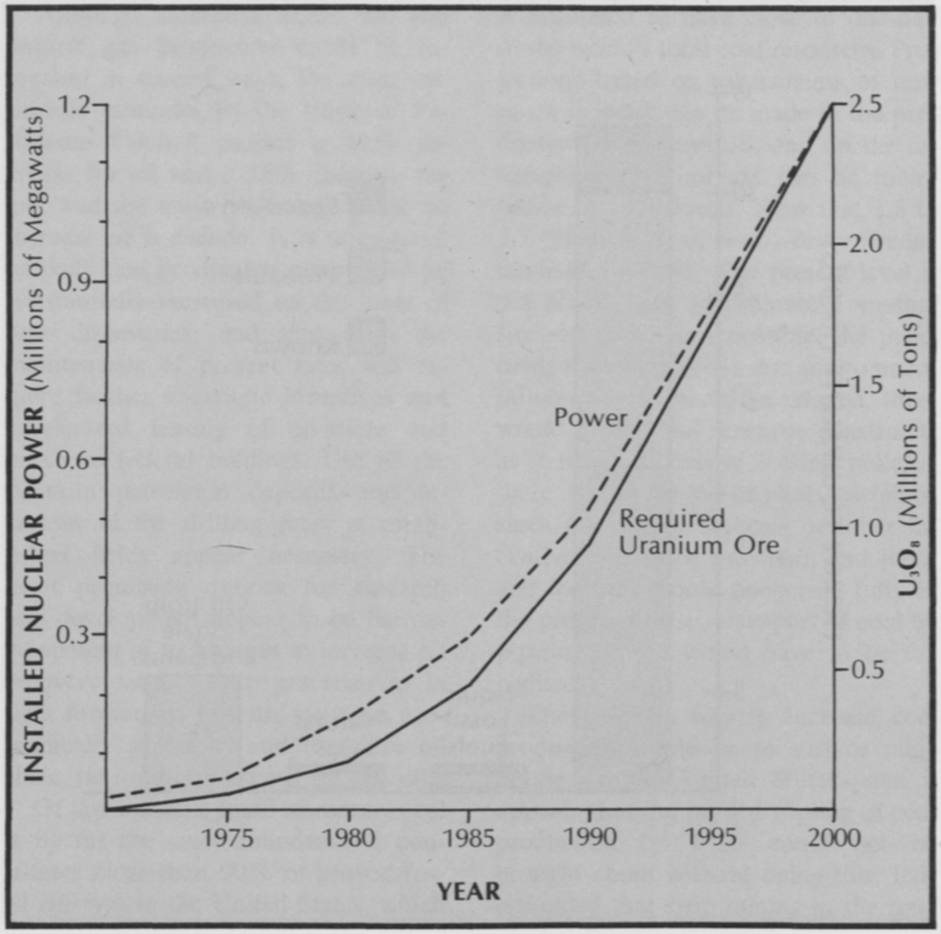
Utilization of additional coal can be made in several ways. One of the quickest and most effective ways to reduce shortfalls in gas and oil is to substitute coal in existing electric utility and industrial boilers and to require that new fossil-fuel-burning plants be built with coal-firing capability. The conversion of coal to liquids or gas is the other obvious route. The main processes considered by the panel are the production of high-Btu synthetic pipeline gas by a modified Lurgi or alternative process; production of clean, more economic low-Btu gas to replace natural gas for industrial purposes; and liquefaction processes to yield boiler fuel or synthetic crude oil.

The balance between supply and demand is also affected, of course, by conservation measures, which could help ease the time situation as well as reduce consumption.

ENVIRONMENTAL AND ECONOMIC FACTORS

Involved in all the fossil-fuel options is the need for environmental safeguards. To make the use of coal acceptable from the standpoint of air pollution, the panel suggested that coal-fired utility plants and, where possible, industrial plants, be located in rural areas and have sufficiently high stacks to meet ambient air standards. For use in urban areas, the coal could be converted to low-sulfur gas or oil or stack scrubbing technology could be employed. Unfortunately, all control technology requires the use of energy, and environmentally desirable methods such as the conversion of coal to low-sulfur gas or liquid are accompanied by energy loss. Environmental considerations are important also in the mining

The anticipated short-term requirements for uranium ore in the United States and the projected growth of nuclear power capability. The ore requirement, given as cumulative amounts, includes that needed for burnup, to inventory new reactors projected to be built, and for stockpiling several years ahead. It is assumed that 80% recycling of plutonium will be adopted in 75% of the plants by 1979, and that 560 tons of U_3O_8 yields 1,000 megawatts of power. The estimates are for LWRs; if HTGRs are built, the figures would be reduced somewhat. Data source: AEC.



of coal. They are the principal obstacle to surface mining, and an immediate need is to investigate restoration methods in arid western regions. Health and safety measures for expanded underground coal mining constitute another area that needs immediate attention. A further environmental concern is the availability of water, particularly for shale oil extraction or coal conversion in arid western regions.

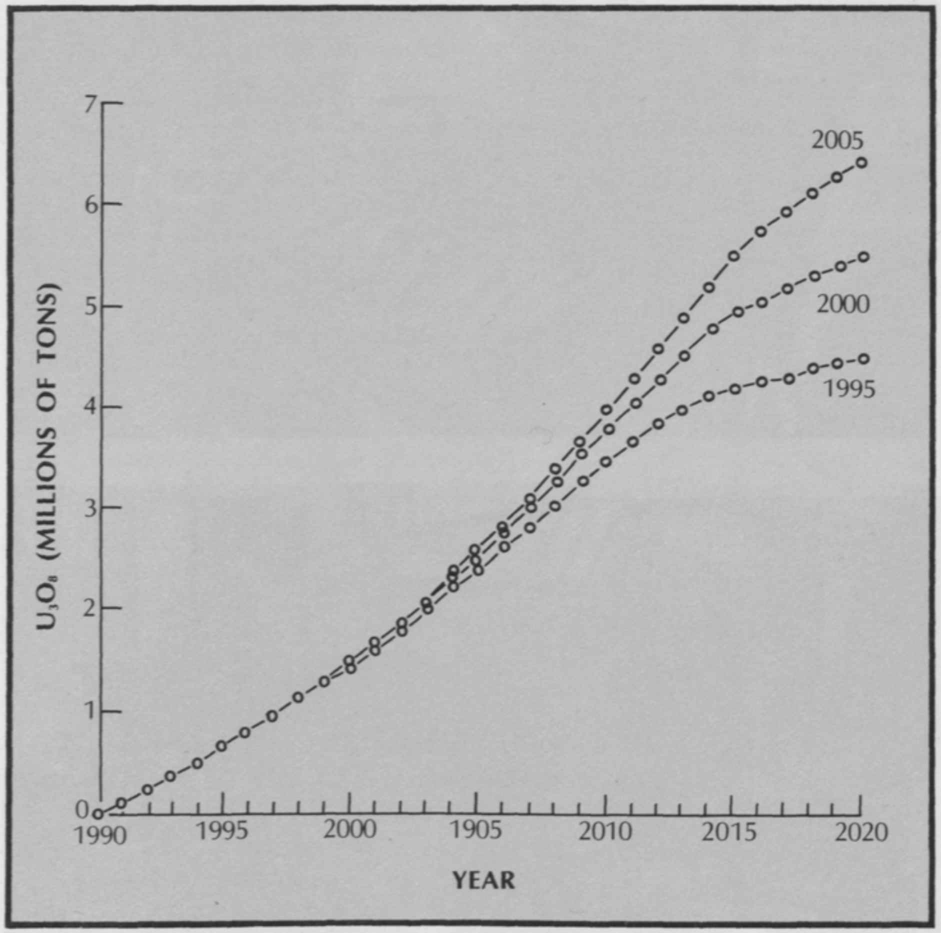
The economic factors involved in all these options are complex, and much development will be heavily dependent on federal policies and provisions. High capital costs, uncertainty about markets and commercial feasibility, and technological risks are involved in enterprises such as the development of a commercial shale oil industry.

Heading the Workshop on the Fossil Fuel Option was William Gouse, Jr., director of the Office of Research and Development, Department of the Interior. The report was prepared by Harry Perry, staff member of National Economic Research Associates. Represented on the panel were industrial, academic, and environmental groups.

THE SHORT-TERM NUCLEAR OPTION

Nuclear power is essential to the United States energy program in the near future and "must not be allowed to falter." This was the position taken as a starting point by the Workshop on the Short-Term Nuclear Option. "The need for nuclear energy is far too great, the level of risk is acceptably low, and the social and economic consequences from loss of the nuclear option are far too troublesome to allow such a circumstance to develop," the panel commented in its report.

Many of the issues involved in the nuclear option were recognized to be more matters of policy than R and D. Licensing and regulatory practices, for example, are closely connected with matters of safety and environmental protection. Decisions on these matters, as much as on technological ones, affect the length of time in which nuclear plants can be built and put into operation (this time span has been increased from an anticipated seven years to ten).



Anticipated United States requirements for uranium ore in the longer term. The amount of U_3O_8 needed is given as cumulative requirements in millions of short tons, beginning in 1990. It is assumed that commercial breeders (using oxide fuel) will be introduced in 1990; the three curves represent estimates based on the introduction of advanced breeders (using carbide fuel) in 1995, 2000, or 2005. Other assumptions: no plutonium recycle in LWRs; demand for electricity to double every fifteen years; additional demand to be satisfied entirely by nuclear power after 2010. Data are based on AEC estimates up to the year 2000, and on calculations of Hans A. Bethe and Chaim Braun of Cornell University for the years after 2000. Projections based on other combinations of assumptions about the dates of introduction of commercial and advanced breeders and about the length of time for doubling of demand are included in the Cornell Report.

The panel was convinced that nuclear power can be safely deployed and that although risk cannot be entirely eliminated, a small risk must be accepted in exchange for a large benefit.

The United States has in operation, under construction, or firmly committed, more than 150 million megawatts of nuclear power. These plants are expected to be in operation by the early 1980s. By 1985, it is expected that nuclear reactors will provide about 280 million megawatts of power and account for 17 to 20 percent of the national energy budget. The energy input through nuclear fuels should correspond to between 400 and 800 million tons of coal annually.

Most of these reactors will be light-water converters, although it is expected that some high-temperature gas-cooled reactors will appear by 1985. The Workshop considered possible effects of breeder reactors on the demand for uranium ore, and concluded that the breeders would be of no help in the short run, although they will be extremely important beyond the year 2000. The earlier they can be introduced, of course, the less pressing the problem of ore supply will become.

The Workshop specifically recommended the following measures: (1) a much firmer resolution of the uranium ore situation; (2) satisfactory demonstration of plutonium recycle, which is essential to stretching fuel supplies so long as the currently used light-water reactors are relied upon; (3) thorough analysis, from the standpoint of safety, of all parts of the nuclear cycle, including the handling of wastes, trans-

Research in many departments of the College is related to the supply, production, and use of energy. Some examples are illustrated.

1. Projects underway in Geological Sciences include studies of underground formations, including geothermal areas, petroleum provinces, and mineral deposits. Professor Sidney Kaufman demonstrates a gravity meter, which can measure extremely small variations in the earth's gravitation field and so help elucidate underground structure. It is sensitive enough to detect the difference in altitude between this campus footbridge and the floor of Cascadilla Gorge below. Other projects of the department include deep seismic reflection profiling (see page 43), which has applicability to oil exploration.

2. The effect of earthquakes on concrete secondary containment vessels for nuclear power plants is being studied by a Structural Engineering group. Principal investigators are Professors Richard N. White (at top of photo) and Peter Gergely. Theoretical studies pertinent to the assessment of transient pressure and thermal effects in nuclear reactor containment vessels are being made by Professor Yih-Hsing Pao of Theoretical and Applied Mechanics.

3. Research related to the possible production of energy by controlled thermonuclear reaction is conducted by College personnel in several departments, largely through the Laboratory of Plasma Studies. Experimental work on plasma heating and confinement is directed by Professors Charles R. Wharton, Bruce Kusse, John A. Nation, and Hans H. Fleischmann. Fleischmann is shown with a magnetic coil configuration for an experiment in the confinement of fusion plasma using trapped relativistic electron beams. Related theoretical work is conducted by Professors Ravindra N. Sudan, Peter L. Auer, and Richard V. E. Lovelace.

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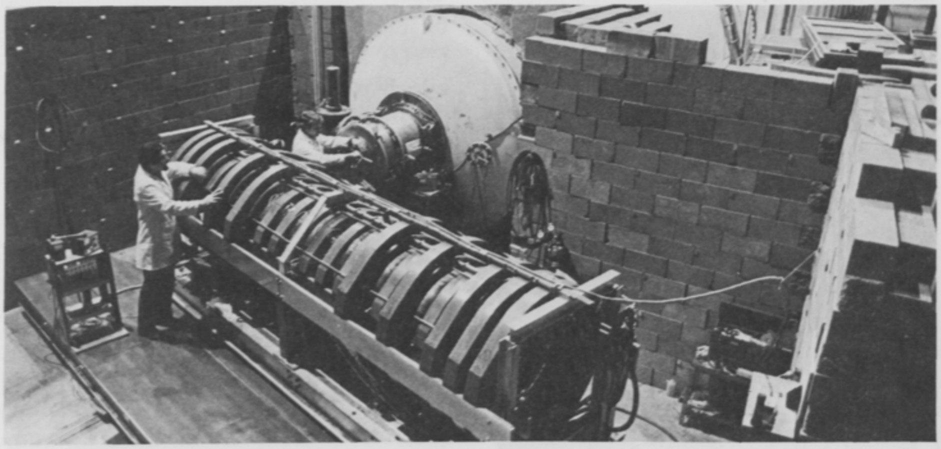

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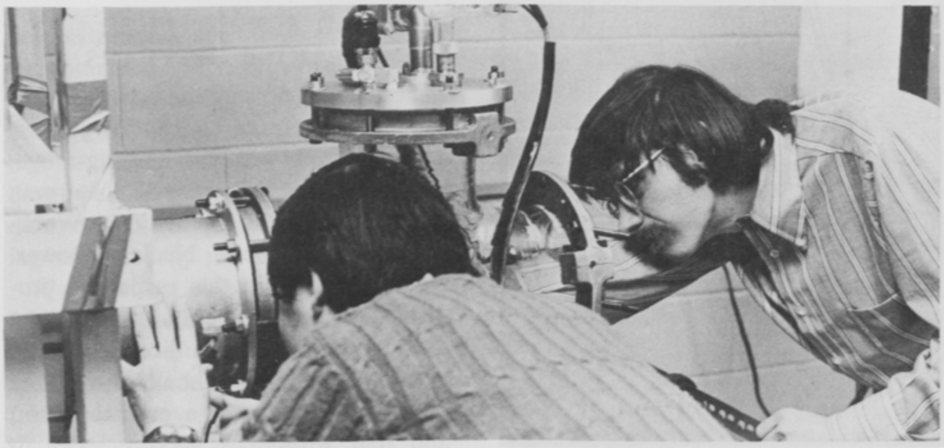

4. High-powered ion beams, which might be used comparably to electron beams for plasma confinement, are being investigated by Stanley Humphries, Jr. (who appears at right in the photo) and Jar-Juey Lee, research associates working with Professor Sudan.

Studies relevant to the use of nuclear and other power plants are in progress in several departments. Environmental Engineering Professors Wilfried H. Brutsaert and James A. Liggett are studying different aspects of circulation, evaporation, and cooling of large bodies of water —research that has relevance, for example, in assessments of ecological effects of power plants on lakes. Professor Franklin K. Moore of Mechanical and Aerospace Engineering is working on the design of cooling towers and siting strategies for nuclear power plants. Agricultural Engineering Professor Donald R. Price is investigating the feasibility of using thermal discharge from power plants for food processing and greenhouse production.

Chemical Engineering research includes work on catalysis, fuel cells, and desulfurization and coal gasification. Other energy-related work is described in the Winter 1974 issue of this magazine, "Options for Engines."

5. Research in Materials Science and Engineering that is applicable to the development of materials for nuclear reactor components includes studies by field ion microscopy of defects produced in metals by irradiation. This work is directed by Professor David N. Seidman; several of his graduate students are shown working in his laboratory. Others in the department who are directing energy-related research are Dieter G. Ast (materials for solar and electrical energy applications), Edward J. Kramer (superconducting and dielectric materials for electrical transmission), John M. Blakely (surface catalysis, of interest in coal conversion technology), Boris W. Batterman and Stephen L. Sass (metal hydrides, of interest for hydrogen storage), Herbert H. Johnson (embrittlement of metals by hydrogen, and stress-corrosion in turbines and boilers), Lutgard DeJonghe (solid electrolytes, of interest for energy storage), and Che-Yu Li (radiative damage in reactor components and high-temperature mechanical properties of metals for turbines and boilers).

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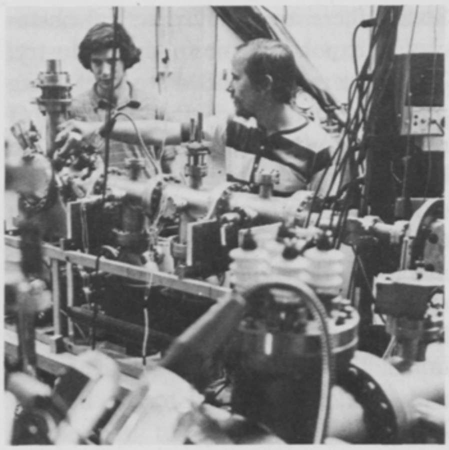
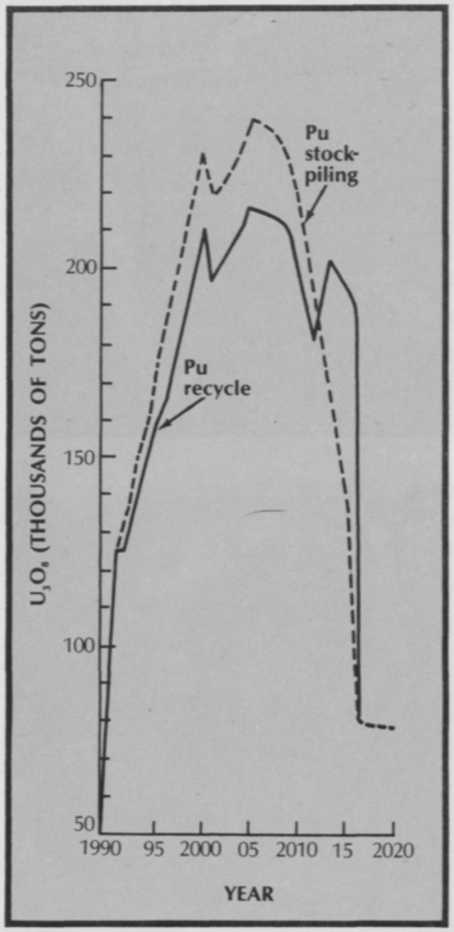


Anticipated annual requirement of the United States for uranium ore. The curves represent estimates calculated on the basis of whether plutonium produced in LWRs will be recycled in these or stockpiled for later use in breeders. It is assumed that commercial breeders will be introduced in 1995 and advanced breeders in 2000. Demand for electricity is assumed to double every twenty-five years. Adapted from the Cornell Report.



port of radioactive materials, and chemical reprocessing, as well as the reactor portion of the cycle; (4) epidemiological studies of the effect of radiation on human population, provided that these are deemed to be feasible; and (5) clear communication to the public of the findings with respect to nuclear safety and low-level radiological exposure.

Research and development priorities were considered to include exploration for uranium and development of mining methods. Members of the panel felt that although there are large potential reserves of uranium in the United States, there are many practical obstacles to expanding the mining industry. They also recommended study of siting problems, particularly the clustering of reactors and reprocessing plants, the building of separative plants, and study of environmental effects of thermal discharge.

This Workshop was chaired and the report prepared by Alvin M. Weinberg, then director of the Oak Ridge National Laboratory and now research and development head at the Federal Energy Office.

THORIUM AS A NUCLEAR FUEL IN THE MIDTERM

Two reactors that appear promising as interim nuclear energy plants after about 1980 and before advanced reactors become available are the high temperature graphite reactor (HTGR) and the light-water breeder reactor (LWBR).

A principal advantage of the HTGR is that it has a better conversion ratio and therefore fuel utilization than a present-day light-water reactor (LWR). Its initial fuel consists of a mixture of essentially fully enriched uranium (^{235}U) and thorium, the makeup fuel, which is converted to ^{233}U upon irradiation and replaces ^{235}U in recycling. The HTGR, in other words, requires over its lifetime less separative capacity and less uranium ore than the LWR. The LWBR, which may or may not prove to be a true breeder, also uses thorium and also extends fuel economy, and it has a further advantage in that some existing LWRs could be converted to LWBRs. Neither of these reactors is sufficient in the long run, however.

NUCLEAR POWER: FUEL FOR MILLIONS OF YEARS

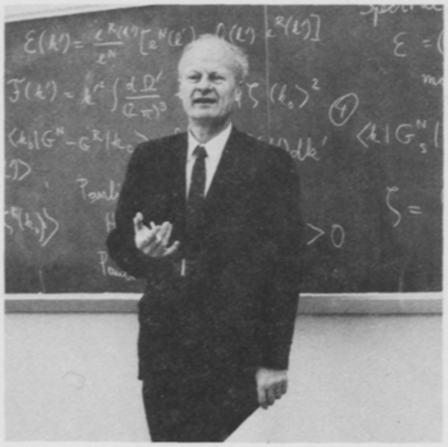
"The fast breeder and the fusion reactor are the only forms of technology now in sight which will give us long-range, ample sources of energy," chairman Bethe wrote in the report of the Workshop on Advanced Nuclear Power. "Their promise in this respect is prodigious: either one would provide a fuel supply for many millions of years."

He coupled this, however, with a warning that time is a crucial factor, and that without a good breeder or fusion reactor the problem of uranium supply may become serious in twenty to thirty years. High-grade ores in the United States are being rapidly depleted, and if lower-grade ores are needed to keep up a supply for light-water reactors, the scale of mining could be very large. The amount of rock needed might be comparable to the amount of coal required for production of an equivalent quantity of energy.

Workshop members concluded that first priority must be given to the development of the breeder rather than a fusion reactor, since feasibility has

Auer

Bethe



Active Cornell faculty participants in the Workshops were Peter L. Auer, who initiated the project and wrote an overview report of the proceedings, and Hans A. Bethe, who served as chairman of the Workshop on Advanced Nuclear Power.

been established for the breeder but not for contained fusion processes. Of possible breeders, the liquid metal fast breeder (LMFBR) is the leading candidate. Liquid sodium has been well developed as a coolant and many sodium-cooled reactors have been working satisfactorily for many years.

Two distinct objectives were seen in LMFBR development—one commercial and one of national concern—and the panel made recommendations it felt would serve both purposes better than current plans would.

The commercial objective is to develop a breeder that is economically competitive with the present-day LWR. A first step in the United States is the demonstration plant (Demo I) now being planned. This should be frankly oriented toward the commercial goal, the panel felt. The main emphasis should be placed on performance of the engineering systems, and maintenance and reliability should be tested. Plant design could be left to the contractors. A further suggestion was that a larger plant, Demo II, be started when the design of Demo I is finished—about four years prior to operational experience.

The second objective, of national concern, which "seems to have been forgotten," is to ensure a continued, ample source of energy. This requires a breeder with a high breeding gain and a low specific inventory (ratio of fissile material to power generated). The panel considered that it is the responsibility of the federal government to assure this second objective, since it is not a commercially viable goal.

Specifically, the need is for a breeder with a *doubling time* (the time it takes for the amount of fissile material to double) that is shorter than the doubling time of the demand for electric power. Demand presently doubles every nine years, and may be expected to increase somewhat, and so the doubling time of a good breeder should be less than ten years. "If and when we have a breeder," the report pointed out, "the breeder industry will have to be started only once, by investing enough fissile material (^{235}U, ^{233}U, or ^{239}Pu) to satisfy the entire power demand at that time. Thereafter, the breeder will automatically produce enough additional fissile material to keep up with expanding power demand. The reactors will consume only fertile material, that is, the abundant isotope ^{238}U or thorium." Use of carbide rather than oxide fuel increases efficiency and appears likely for advanced breeders.

Because of the time factor involved in development of the LMFBR, the panel also recommended the examination of interim measures such as plutonium recycling in LWRs, greater use of the HTGR, and the Canadian heavy-water moderated thorium burner.

Also called for by the panel is a materials research program, "the most important requirement" for development of the LMFBR. This should include, in order of importance, research on alloys for cladding and subassembly cans, on advanced fuel, and on improved methods of reprocessing. Specific recommendations were outlined.

The fact that fast breeders contain much more than a critical mass of fissile material has been the basis of apprehension about the possible results of an explosive accident. Research of the past ten years has greatly reduced fears, however. Calculations show that in the course of a hypothetical accident, a strong negative temperature coefficient of reactivity, due to the Doppler effect, would prevent explosive buildup of pressure, so that reactor fuel would not escape the primary reactor containment. This Doppler effect has been carefully measured in critical assemblies and in a reactor.

In spite of this and other reassuring information, the problem of safety was considered so basic that further intensive work, especially on the important problem of safety in normal operation, was recommended. This problem must be "attacked from all angles and solved quickly," according to the report. "Otherwise, the progress of LMFBR deployment could well be paced by unresolved safety issues rather than technological advances." Specific suggestions for study were made.

FUSION AND OTHER LONG-RANGE OPTIONS

While the feasibility—scientific as well as engineering—of a fusion reactor has not yet been demonstrated, its inherent advantages, including a virtually infinite supply of very low-cost fuel, justify continued research, particularly of a fundamental nature. The current approaches to fusion lie in two categories, magnetic containment and laser fusion. Contributing to issues surrounding research in these areas is the fact that laser fusion has military as well as potential commercial applicability.

Both fission in a breeder and fusion rely on virtually inexhaustible resources: uranium and thorium in a breeder economy and lithium and deuterium in a fusion economy. Other possible energy sources—the sun and geothermal energy—are basically renewable, although much research will be needed to make them practicable.

INSTITUTIONAL PATTERNS IN ENERGY R AND D

The panel on Energy Research and Development Institutional Patterns, headed by Thomas O. Paine, senior vice president of the General Electric Company, made the basic assumption that the United States will adopt a flexible policy requiring an infrastructure involving government, industry, the universities, and research institutes. The establishment of a single goal-oriented national agency for energy R and D was endorsed.

Among specific recommendations was the attainment of "an improved data base on which sounder standards of licensing and environmental and safety regulations can be founded and providing for more rational analyses of the effects of trade-off decisions."

A strong technology assessment program was recommended. This program would include "work in depth on the economics, world trade, foreign policy, environmental, social, regulatory, legal and administrative aspects of future alternate national energy scenarios that successful R and D programs may make possible."

"The success of the goal-oriented organizations proposed," the report concluded, "will be judged . . . by the degree to which a credible capability for national self-sufficiency in clean energy in the period from 1975 to 1985 is demonstrated. The goal is to build an industry."

THE HYDROGEN ECONOMY: SOLUTION TO THE ENERGY PROBLEM?

by Simpson Linke

History will record this decade as the period when the precarious nature of man's energy supply became universally understood. We now realize that our fossil-fuel resources are finite, that these precious materials are far too valuable simply to be burned as fuel, and that environmental concerns are ignored at our peril. These factors have focused attention on the need for an abundant, clean, economical synthetic fuel that may be obtained without sacrifice of national energy self-sufficiency.

Hydrogen is a prime candidate for this role in our energy future. It assumes even greater importance when we recognize that this gas may also be used as the means for economical transmission and storage of energy, as well as for direct conversion into electrical energy by means of the hydrogen-oxygen fuel cell. The integrated concept of the multiple application of this form of energy has become known as the *Hydrogen Economy.*

If the use of hydrogen as an energy medium appears to be such a good solution to our energy problems, natural questions arise as to why the Hydrogen Economy has not been adopted by the energy industries. Why do we not extract all of our fuel needs from the "limitless" waters of the sea? Why not convert "free" solar energy to electricity and use it for the large-scale production of hydrogen by electrolysis of water? Why not substitute hydrogen for natural gas in our existing pipeline networks? Can the Hydrogen Economy compete with the All-Electric Economy? Is hydrogen a potential jet-aircraft fuel?

Proponents of the Hydrogen Economy—an enthusiastic and optimistic lot—believe that most of the developments suggested by such questions are inevitable, and will be implemented by the year 2000. Others are more pessimistic, and while perhaps admitting the possibility that the Hydrogen Economy is inevitable, see enormous technical and economic difficulties that must be surmounted. In the Cornell International Symposium and Workshop on the Hydrogen Economy that was held on the campus in August, 1973, advocates and skeptics gathered together for the first time to debate these issues. The results of that confrontation will be reported in a forthcoming set of Proceedings.

The potential impact of the Hydrogen Economy upon the future of transportation, and the nature of the concept, were discussed by Cornell Professors P. C. T. de Boer and William McLean in an article in the Winter 1974 issue of this magazine. The present article presents a summary of the current status of the concept as it relates to the general release and utilization of energy.

A UNIVERSAL, ABUNDANT SOURCE OF ENERGY

Hydrogen, the most plentiful element in the universe and the ninth most abundant on earth (on a weight basis), is an odorless, colorless, tasteless gas with a name derived from the Greek for "producer of water." In 1766 Cavendish called the gas "inflammable air," pointing out a characteristic that is immediately understood today when Hydrogen-Economy proponents refer to themselves as members of the "H_2indenburg Society." The gas is known to exist in stars, in comets, in

Table I

HYDROGEN AS COMPARED WITH SEVERAL OTHER FUELS*

Fuel	Heat of Combustion (Btu/lb.)	Density		Ease of Storage (relative ranking)
		Gas (lb./ft.^{3})†	Liquid (lb./ft.^{3})	
Hydrogen (H_2)	51,600	0.005	4.4	4 (liquid)
Methane/Natural Gas (CH_4)	21,500	0.041	25.9	3 (liquid)
Gasoline (C_8H_{18})	19,100	—	43.8	1
Methanol (CH_3OH)	8,600	—	49.7	2

* Note that hydrogen has a clear advantage as a fuel for aircraft, since fuel value, on a weight basis, is 2.7 times greater for hydrogen than for gasoline. On the other hand, the much larger volume required for hydrogen storage is one of the principal drawbacks to the development of the hydrogen automobile. Table adapted from *Hydrogen and Other Synthetic Fuels,* report TID-26136 of the Federal Council on Science and Technology, September 1972.

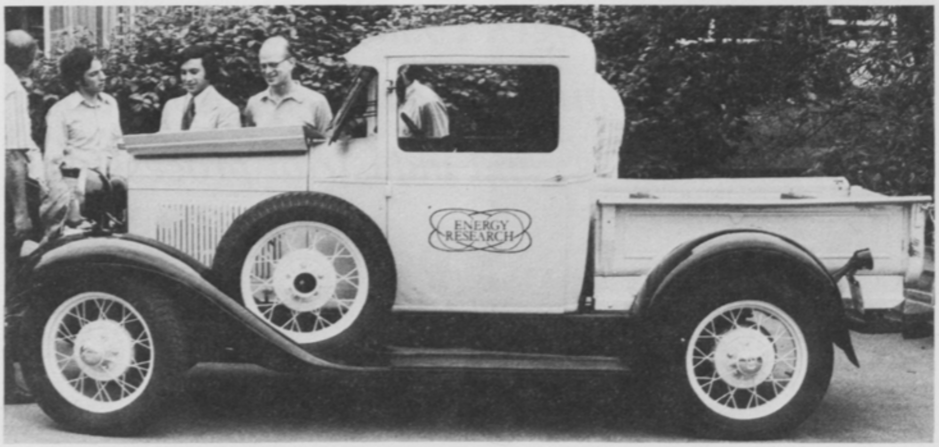
† At standard cubic foot (scf) conditions.

the sun, and in our upper atmosphere. On earth it occurs naturally to some extent in gases liberated by volcanoes, and it is also released by the fermentation process. Most of the earth's hydrogen, however, is combined with other elements: with oxygen to form water, for example, and with carbon to form hydrocarbons, including coal, petroleum, natural gas, and methanol. Hydrogen also appears with other organic components and is present in practically all animal and vegetable matter. Unfortunately, it is not possible to dig a "hydrogen well" and find the gas in pockets beneath the earth's surface, as is done for natural gas and oil. It must be released from its naturally occurring compounds, and for this purpose it is necessary to apply external energy.

The future of the Hydrogen Economy rests upon solutions to the problems posed by the efficient conversion of this external energy to hydrogen, and thence into useful work. An example will illustrate the nature of the difficulties.

Suppose that it is desired to electrolyze one pound of liquid water into the equivalent number of standard cubic feet (scf) of hydrogen and oxygen at room temperature and atmospheric pressure. Assuming that the conversion occurs at 100 percent efficiency, about 2 kilowatt hours (kwh) could be required to do the job, and 20 scf of hydrogen would be produced. Since present-day electrolyzers have an efficiency of around 65 percent, about 3 kwh of electrical energy would actually be needed, in direct-current form. A modern fossil-fuel steam plant operates at an efficiency of 40 percent. Transmission and rectification losses reduce the net efficiency to about 35 percent. Thus, the production of the necessary electrical energy would require fossil fuel having an equivalent energy content of 8.5 kwh. The overall efficiency of conversion is therefore about 23 percent. For this example, it should be noted that approximately 10 scf of oxygen would also be released as a valuable byproduct.

Some physical data for hydrogen, and a comparison of its characteristics



A hydrogen-powered vehicle was brought to the Cornell campus by delegates to the Cornell International Symposium and Workshop on the Hydrogen Economy last summer. The bright yellow and black 1935 Model A Ford pickup was brought by truck from Provo, Utah by representatives of the Energy Research Corporation. The modified vehicle carries its fuel in two hydrogen cylinders in the truck bed, and has a range of about twenty miles. The group pictured with the truck includes Oren Bloom, at left, a Ph.D. student in environmental engineering and electrical engineering.

with those of several other fuels, are given in Table I.

COMMERCIAL PRODUCTION OF HYDROGEN TODAY

Hydrogen is produced commercially in fairly large quantities for use by various industries, but the total output is only about one percent of the amount that would be required to fuel a universal hydrogen economy. A number of production techniques are employed, including the following:

(1) Steam-hydrocarbon reformer process
(2) Steam-water-gas process
(3) Electrolysis of water
(4) Steam-iron process
(5) Thermal decomposition of hydrocarbons
(6) Steam-methanol process

In the recent past, the most attractive scheme has been the steam-hydrocarbon reformer process, where the source of energy has been natural gas. The overall conversion efficiency is about 70 percent. Except for electrolysis, all of the listed commercial processes depend upon the combustion of fossil fuels. Consequently, the resultant hydrogen cannot meet the rigid requirements previously set forth for a "clean" synthetic fuel. If the end product is electricity from the combustion of fossil fuel, the direct process goes at 40 percent. If the process converts natural gas to hydrogen and then burns the hydrogen to produce steam and electricity, the overall efficiency is only about 28 percent. On the other hand, if an efficiency of 100% in the electrolysis of water could be approached, the future of the Hydrogen Economy would be very promising, provided that clean and relatively economical sources of electric energy are available.

SOLAR ENERGY FOR ELECTROLYSIS OF WATER

It is interesting to note that approximately one cubic mile of water contains enough energy in the form of hydrogen to satisfy all of the present annual demand in the United States. Further, when the energy is released by recombination of the hydrogen with the equivalent amount of released oxygen, most of the water is returned to the environment. This "closed cycle" effect makes the hydrogen energy concept very attractive indeed. The missing ingredient is the clean energy source required to separate the hydrogen and oxygen from the readily available water supply. The ultimate ideal source, of course, is direct use of solar energy. This prospect is very appealing, and a variety of schemes have been proposed, but the physical and economic obstacles are formidable.

For solar-power-to-electricity-to-electrolysis, the solar-cell efficiency is of the order of 10 percent, and the unit cell cost is usually estimated at about $50,000 per kilowatt, or about 200 times the total cost of an equivalent fossil-fuel steam plant. Other difficulties include the necessary limitation of solar energy conversion to daylight hours, the lack of high-density storage-battery capability, and the necessity for large amounts of sun-drenched real estate. For a 10,000-megawatt, continuously operated generating station with photovoltaic cells of 10 percent efficiency and electrolyzers that are 100 percent efficient, approximately

"Hydrogen could become the ideal, pollution-free synthetic fuel for transportation, space heating, and industrial processing."

200 square miles of stationary collector surface *alone* would be required. This estimate assumes eight hours of sunlight, so that 30,000 megawatts of solar-cell installation plus battery or equivalent storage facilities are required for around-the-clock operation. The solar constant is taken to be 500 watts per square yard (50 percent of the Arizona average) to account for the movement of the sun.

Additional space would be required for the electrolysis, water-pumping, water-storage, and gas-storage facilities, and possible gas-liquefaction equipment. Feed water for the plant would be a moderate five billion gallons per year, or about twice the annual requirement for the City of Ithaca.

While "solar farms" of this magnitude are certainly feasible, the present-day capital costs would be staggering, operation and maintenance is likely to be highly energy-intensive, and there is considerable uncertainty as to possible impact on the desert environment. The one bright spot for this venture is the possible creation of a large market for the solar cell, thereby stimulating development of inexpensive production techniques which should reduce the cost to more reasonable values. Research and development efforts designed to produce a more efficient cell would also be encouraged.

THE THERMAL CRACKING OF WATER—AN ALTERNATIVE

An alternative to the technique of electrolysis using solar energy is to attempt "thermal cracking" of water by concentrating solar rays through use of Fresnel lenses and heliostats in the manner of high-temperature solar furnaces. Direct thermal cracking without catalysts requires temperatures of the order of 2,500°C, a level that is readily obtained in a solar furnace. Unfortunately, the realization of this process is very difficult, principally because of severe materials problems at these temperatures. Separation and collection of the gases would be a challenging task, and, as in the case of electrolysis, the process would require large land areas and huge investments in complex optical gear and auxiliary equipment. The necessity for optical "tracking" of the sun would add major dimensions to the operation, maintenance, and cost of the system. Proposals have been made for a lower-temperature system, in the range of 1,500°C, where the materials problems are less severe; however, the less-than-one-percent efficiency of the suggested designs presents a serious economic barrier to early success.

A relatively new idea for the thermochemical cracking of water has excited attention around the world in recent years. Proposed in 1969 by G. de Beni and C. Marchetti of the EURATOM-CCR research establishment in Ispra, Italy, the technique would use heat of about 750°C from high-temperature nuclear reactors to decompose water in a catalytic reaction involving bromine and mercury. A block diagram that displays the elements of the initial Mark 1 process is given in Figure 1. Since the announcement of the Ispra program, other laboratories in this country and abroad have started research on similar reactions. The specific promise of this technique is that the theoretical efficiency is about 75

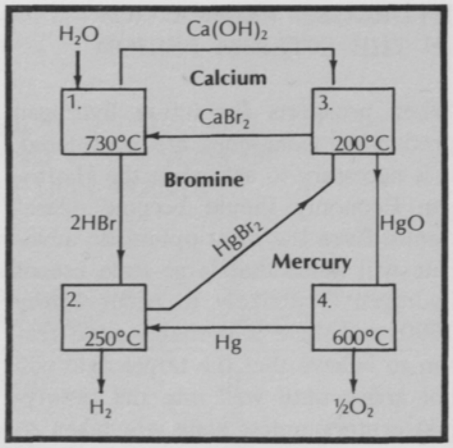


Figure 1. Diagram showing the elements of the initial Mark 1 process for thermochemical cracking of water proposed by EURATOM-CCR in Italy. The catalytic reaction would proceed with heat from a nuclear reactor as the energy source. From "Hydrogen and Energy" by C. Marchetti, published in Chemical Economy and Engineering Review, *Tokyo, Japan, 1973.*

percent, as compared with an overall efficiency of 35 percent for a cycle of nuclear heat to electricity to 100 percent-efficient electrolysis.

Assuming that the problems related to the safety of nuclear reactor operation can be solved successfully, and that the breeder reactor will become a reality in the next decade, nuclear–thermochemical cracking of water could hold the key to the establishment of the Hydrogen Economy, particularly if theoretical efficiency can be attained. The principal advantage would be that a versatile, clean fuel, as well as electricity, would be derived from nuclear energy. Since it is likely that most transportation, space heating, and industrial processing will continue for some time to make heavy demands upon a fuel supply, rather than depending on electricity, the availability of hydrogen as an alternative to dwindling natural gas reserves is decidedly attractive. Further, the reduction of waste heat from the present 60 percent level to 25 percent would constitute a great boon to the environment.

Achievement of these worthy goals will require years of chemical engineering and materials research and development. It will be necessary to determine the optimum chemical reactions. At Ispra, for example, Mark 1 has been superseded by more advanced cycles, with Mark 9 as the most recent choice. Large-scale chemical auxiliaries must be developed. It is not clear at this time whether the overall economics will be more favorable for these processes than for the straight electrolytic technique, in spite of the high efficiencies that may be possible. It is significant to note that no complete thermochemical cracking cycle has yet been demonstrated on an integrated basis.

THERMOCHEMICAL CRACKING VERSUS ELECTROLYSIS

Advocates of the Hydrogen Economy who are electrochemists seize upon this hypothetical nature of thermochemical cracking of water and are quick to point out that electrolysis is a proven technology. Bolstered by their firm belief in the eventual realization of the 100-percent-efficient electrolyzer, they make a strong argument for the future establishment of electrolytic hydrogen as the most efficient and most economical process, with electricity from nuclear heat as the prime energy source. If electrolytic cells are operated at elevated temperatures, energy from the heat source contributes to the energy balance of the cell. Thus it is claimed that the process achieves a conversion efficiency of over 100 percent, based on electrical input, assuming that additional energy in the form of heat is added to the electrolyzers. Consequently, large-scale research and development directed to the improvement of electrolyzer efficiency is considered to be a high-priority item.

Present-day commercial production of electrolytic hydrogen is generally confined to those areas served with large amounts of hydroelectric power. Since the further exploitation of potential hydro sites cannot contribute significantly to our total energy needs in the future, the promise of the electrolytic technique necessarily depends upon nuclear power in the middle term, with solar and possibly fusion power the prime candidates for the far term.

"... an abundant, clean, economical synthetic fuel that may be obtained without sacrifice of national energy self-sufficiency."

HYDROGEN PRODUCTION IN THE INTERIM PERIOD

When prospects for future hydrogen production techniques are considered, it is necessary to ask when the Hydrogen Economy should become operational. Even the most optimistic advocate will agree that large-scale use of hydrogen is unlikely to occur before 1990, and there is probably good reason to believe that the target date will not arrive until well into the twenty-first century unless steps are taken to encourage limited acceptance of the concept in the very near future.

A move to hydrogen could have a profound effect upon near-term energy policy, particularly with regard to the utilization of coal. Advanced electrolyzers, solar-driven electrolysis, and thermochemical cracking of water will, no doubt, fully establish the Hydrogen Economy if a thriving hydrogen market provides the necessary incentives. Steps could be taken toward creation of this market by manufacturing hydrogen from coal or lignite for an interim period until the cleaner methods become operative.

A strong case for the interim production of hydrogen from lignite or bituminous coal is presented in the September, 1972 report of the Synthetic Fuels Panel of the Federal Council on Science and Technology R and D Goals Study. The argument is developed around an assumption that 7 to 8 percent of the total United States energy demand for the year 2000 would be supplied by hydrogen converted from solid fossil fuel. Lignite is the preferred fuel because of its low sulfur content (78 percent of the deposits contain less than 0.8 percent sulfur) and because of the possibility that uranium could be recovered from the ash. The annual lignite requirement to satisfy this demand would be about 1.4 billion tons. Since there are more than 300 billion tons in available reserves, mostly in western North Dakota, the supply would be more than adequate to establish the Hydrogen Economy until the clean energy sources of the future became available. The report suggests that the North Dakota area could become the hydrogen supply center for the nation in much the same way that the Gulf Coast is the major supply area for natural gas at the present time.

Comparative capital and operating costs for a plant yielding 2,500 tons per day are given in Table II. The total requirement would be 137 plants of this size, with an estimated lifetime of thirty years. The first plant could probably be in service by 1985 if the concept is adopted.

Since it is generally recognized that transfer to the Hydrogen Economy must be a gradual process, the report suggests that a portion of the hydrogen initially produced should be transported via hydrogen pipelines to areas with iron-ore deposits for iron reduction, and some should be used to furnish general process heat for industry. The remaining gas could be brought to the eastern coal fields, also by pipeline, for use in the process of coal gasification to high-Btu synthetic gas. This procedure would save from one-third to one-half of the coal, since this much would otherwise be needed for running the gasification process. The coming scarcity of natural gas will undoubtedly encourage adoption of this scenario to the extent that all hydrogen

Table II
COMPARATIVE COSTS AND EFFICIENCIES OF HYDROGEN PRODUCTION PLANTS*

Process	Capital Cost (10^6 dollars)	Annual Operating Cost† (10^6 dollars)	Heat-Energy Recovery Efficiency (percent)
Steam-methane reformer	53.7	102.7	70
Steam-oxygen: lignite	102.5	121.0	50
Steam-oxygen: bituminous coal	126.1	108.8	50

* These data refer to a productive capacity of 2,500 tons per day. Note that the steam-methane reformer process is a well established industry, while modern production from coal and lignite is in its infancy. Process development could improve efficiency. The expected scarcity and increase in price of natural gas may also help stimulate the production of hydrogen from coal or lignite. Table adapted from *Hydrogen and Other Synthetic Fuels*, report TID-26136 of the Federal Council on Science and Technology, September 1972.

† Total annual operating costs, including 15% fixed charges, are based on 1972 costs of 60¢ per million Btu for natural gas and $7 per short ton for coal and lignite.

production in the nation could convert to the lignite process.

It is quite likely that in addition to supplying the needs of conventional hydrogen-based industries and coal gasification plants, substantial amounts of hydrogen will be diverted to the full implementation of some current experimental activities related to the more general elements of the Hydrogen Economy. These include fuel cells, catalytic heaters, jet-aircraft fuel, hydrogen-powered automobiles, and many others.

FACTORS OF TRANSMISSION, DISTRIBUTION, AND USE

Regardless of whether hydrogen is to be produced by solar, nuclear, or fossil-fuel processes, the construction of "central station" facilities seems indicated because of the technological and economic advantages of large-scale energy sites. Consequently, the efficient transmission of hydrogen from the possibly remote generation points to the load centers is a matter of great importance in the establishment of the Hydrogen Economy. Once the energy is delivered, distribution and utilization must also be accomplished at minimum cost and with maximum reliability. It is on these points that the potential conflict with the all-electric economy will be resolved. Decisions will be made on the basis of a comparison of the relative merits of these two methods of bringing energy to the ultimate consumers.

As it happens, the transmission of hydrogen gas is a relatively well established technology. An extensive hydrogen pipeline has been in operation in Germany for many years; and, before the advent of natural gas, the distribution of "coal gas" or "town gas," which contained up to 50 percent hydrogen, was common in the United States. Hydrogen Economy advocates think that long pipelines, similar to the present natural-gas networks, may be used for the transmission of hydrogen. Although hydrogen has only about one-third the energy per scf that is contained in an equivalent volume of natural gas, it has only one-third of the density of natural gas; by the appli-

Table III

COMPARATIVE COSTS OF VARIOUS TRANSMISSION MEDIA*

Transmission Medium	Power (10^6 Btu/hr.)	Pipe or Line Size	Capital Cost per 100 Miles (10^6 dollars)	Operating Cost per 100 Miles† (cents/10^6 Btu)
Hydrogen	21,000	36-in. pipeline	68**	5.7
Natural Gas	21,000	36-in. pipeline	62**	5.1
Electricity: Superconducting Line	13,600	4,000 MVA line	140	19.3
Electricity: Overhead Line	8,500	2,500 MVA, 750 KV	30	8.3
Electricity: Underground Cable	8,500	2,500 MVA, 345 KV	300	~100

* Adapted from *Hydrogen and Other Synthetic Fuels,* report TID-26136 of the Federal Council on Science and Technology, September 1972.

† Assumptions: 100% utilization, 15% fixed charges, operating power cost of 6 mills per KWh.

** Pipeline costs may vary widely, depending upon terrain, congestion, etc.

cation of increased gas pressure and compressor horsepower, it would be possible to transmit almost the same total amount of energy in a given pipeline, with only a small increase in cost (see Table III). The problem of hydrogen embrittlement of steel under high pressure may require research, however. It will also be necessary to develop hydrogen compressors that can operate at pressure levels well above those now attainable.

Further examination of Table III reveals the obvious advantages of gas over electric transmission from the standpoints of bulk energy and cost. Another factor, not indicated in the table, is that of long-distance capability of the gas pipeline. Transcontinental natural-gas pipelines are a reality today and, provided that the problems of high-pressure transmission are solved, there is no major obstacle to the movement of bulk hydrogen by pipeline. The alternating-current lines designated in the table are limited to a few hundred miles and so have substantially less energy-transport capability. The development of the high-voltage-direct-current (HVDC) transmission line, also not included in Table III, may create significant changes in this comparison, however. HVDC overhead lines and underground cables could transmit power for distances comparable to those of gas lines, and the potential HVDC superconducting line may be able to match, and even exceed, the energy-transport capability of a pipeline of comparable cost.

Of course, it must not be forgotten that the major drawback to the use of the hydrogen pipeline as a transmission medium is that if electricity is to be the end product, conversion must take place at the receiving end. At present levels of technology, the maximum conversion efficiency attainable is 40 percent, whether by steam plant or by fuel cell. Because of the relatively low efficiencies of this conversion and of the initial conversion of other forms of energy into hydrogen, it is clear that electric transmission is still more economical—in spite of the data in Table III—if the form of energy delivered is to be electrical.

"... one cubic mile of water contains enough energy in the form of hydrogen to satisfy all of the present annual demand in the United States."

If, however, the energy can be delivered and utilized in the form of gas, the transmission economics may swing in favor of the Hydrogen Economy. A major factor is the projected cost of new electric distribution extensions, in view of the general trend in most urban areas to place distribution mains underground. Gas pipelines can be installed underground much less expensively. A temporary economic drawback to the adoption of hydrogen as a fuel would be that the customer would have to sustain initial appliance costs when converting from natural gas.

A recent comparison of the relative economics of several alternatives is given in Table IV. These projections, for the year 2000, include costs of generation, transmission, and distribution. It is interesting to note that the proposed interim solution of hydrogen derived from coal is predicted to be the most economical program to follow. Also, the least costly way of supplying energy in the form of electricity is estimated to be the system of producing hydrogen with use of coal and converting it to electricity with fuel cells.

Table IV

PROJECTIONS OF ENERGY DELIVERY COSTS FOR THE YEAR 2000*

Energy System	Energy Form	Delivered Cost (dollars/10^6 Btu)
Nuclear to Electricity	Electricity	6.89
Nuclear to Hydrogen†	Gas	6.54
Nuclear to Hydrogen to Electricity via Fuel Cell	Electricity	9.68
Coal to Hydrogen**	Gas	1.98
Coal to Hydrogen to Electricity via Fuel Cell	Electricity	5.12

* Adapted from "The Hydrogen Economy—a Utility Perspective" by M. Lotker, E. Fein, and F. J. Salzano: a paper presented at the IEEE Power Engineering Society Winter Meeting in New York City in January 1974.

† Advanced electrolysis technology would reduce this cost about two dollars.

** Cost of coal is assumed to be $8 per ton.

THE IDEAL SYNTHETIC FUEL OF THE FUTURE?

This brief survey of the Hydrogen Economy has been limited necessarily to a few high points. The many technical and economic questions that are pertinent to the complete development of this multi-faceted topic are being given thorough attention by an increasing number of investigators who have come to believe that this concept may indeed shape the future of energy utilization. Hydrogen *could* become the ideal, pollution-free synthetic fuel for transportation, space heating, and industrial processing. It offers great potential for convenient storage and for economical and esthetic energy transmission. It could provide energy in a renewable form and eventually free us from the necessity of burning carbon compounds.

Perhaps the principal result of our present struggle with the energy problem will be the realization that the high cost of fossil fuels will cause the Hydrogen Economy to become economically attractive much sooner than could have been reasonably expected.

Simpson Linke, Cornell professor of electrical engineering, has been active recently in energy research and development studies at the national as well as the university level. As part of his activities at Cornell, he is serving as co-principal investigator of the engineering component of the Cornell Energy Project, which is sponsored by Research Applied to National Needs (RANN), a directorate of the National Science Foundation (NSF). In the summer of 1973, Linke organized and chaired the Cornell International Symposium and Workshop on the Hydrogen Economy, as part of the Cornell Energy Project. This past fall he coordinated the Cornell Workshops on the Major Issues of a National Energy Research and Development Program, sponsored by the Atomic Energy Commission, and supervised the subsequent publication of the report of these workshops (see the summary on page 2).

Linke joined the faculty of the School of Electrical Engineering in 1949, and has taught in the areas of electric energy systems and power system analysis. Research in which he has participated includes studies of dielectric breakdown phenomena in high vacuum, the generation and control of high-energy ultra-fast electron discharges, and the generation and characterization of relativistic electron beams. In the 1950s he served as supervisor of the Cornell A-C Network Calculator Facility, and since 1968 he has been assistant director of the Laboratory of Plasma Studies. He has spent sabbatic leaves with the Philadelphia Electric Company and, in 1971–72, as program manager in the Division of Advanced Technology Application of NSF (RANN). During this leave he was also a member of the Technical Group on Electrical Transmission and Systems of the Federal Council on Science and Technology Energy R and D Goals Study, a project cited in this Quarterly *article.*

He holds the B.S. degree in electrical engineering from the University of Tennessee, and the M.E.E. from Cornell. He is a member of the Institute of Electrical and Electronics Engineers, the American Association of University Professors, the International Conference on Large High Voltage Electric Systems (CIGRE), and the honorary societies Eta Kappa Nu and Sigma Xi.

THE ENVIRONMENTAL IMPACT OF NUCLEAR ENERGY

by K. Bingham Cady

Fortunately for the nation, nuclear energy technology had an early development in the United States: this industry will be essential in meeting the rising need for electrical energy in the next several decades. The commitment to nuclear power requires, however, that we recognize and plan for the accompanying biological and environmental costs.

Because the nuclear industry, unlike other energy-producing industries, is subject to strict federal regulation and public scrutiny, the expansion of nuclear capacity requires a general understanding of what the dangers are, and a way of assessing their magnitude. At the University, largely through the Cornell Energy Project, sponsored by the National Science Foundation, scientists and engineers have participated in studies designed to quantitatively assess nuclear hazards. Results show that the outlook for nuclear energy is extremely good when its costs and hazards are compared with others associated with the long-term energy problem: the biological and environmental costs of fossil fuel utilization, vulnerability to coal-mine strikes, and the growing dependence on foreign petroleum.

THE NEED FOR NUCLEAR ENERGY IN THE U.S.

In the United States, the demand for electric energy has been growing at a rate of five to seven percent a year for several decades, and most observers believe it will continue to increase at a similar rate over the next two or three decades before beginning to level off at the end of the century. The decrease, about two percent, in electricity consumption this winter was a result of mild weather and voluntary and forced conservation, and is not expected to be the beginning of a long-term trend. The reason for this is that the growing demand is real and, moreover, one that the nation will be able to meet. Electricity shortages will not have to be borne because the basic fuels needed for the production of electricity—coal and uranium—are domestically available and relatively cheap and abundant compared with the fuels currently needed for home heating and transportation—natural gas and petroleum.

Meeting the demand for electricity with coal and uranium will take a concentrated effort by the government and the coal and nuclear industries. Coal production over the next decades can be expected to be limited, though not severely, by the time required to manufacture drag lines and mining machinery, by requirements for the reclamation of stripped land, by the necessity for increased mine safety, and by the availability of miners and mining engineers. Similarly, the use of nuclear energy will depend on the ability of manufacturers to produce nuclear steam-supply systems and large pressure vessels, and on the availability of nuclear engineers and skilled field construction labor. An important role of the universities in this expansion will be in the education of nuclear and environmental engineers and scientists.

The installation schedule for large electric power reactors in the United States is shown in Figure 1. There are, as of April 1974, forty-four reactors operable, fifty-four under construction,

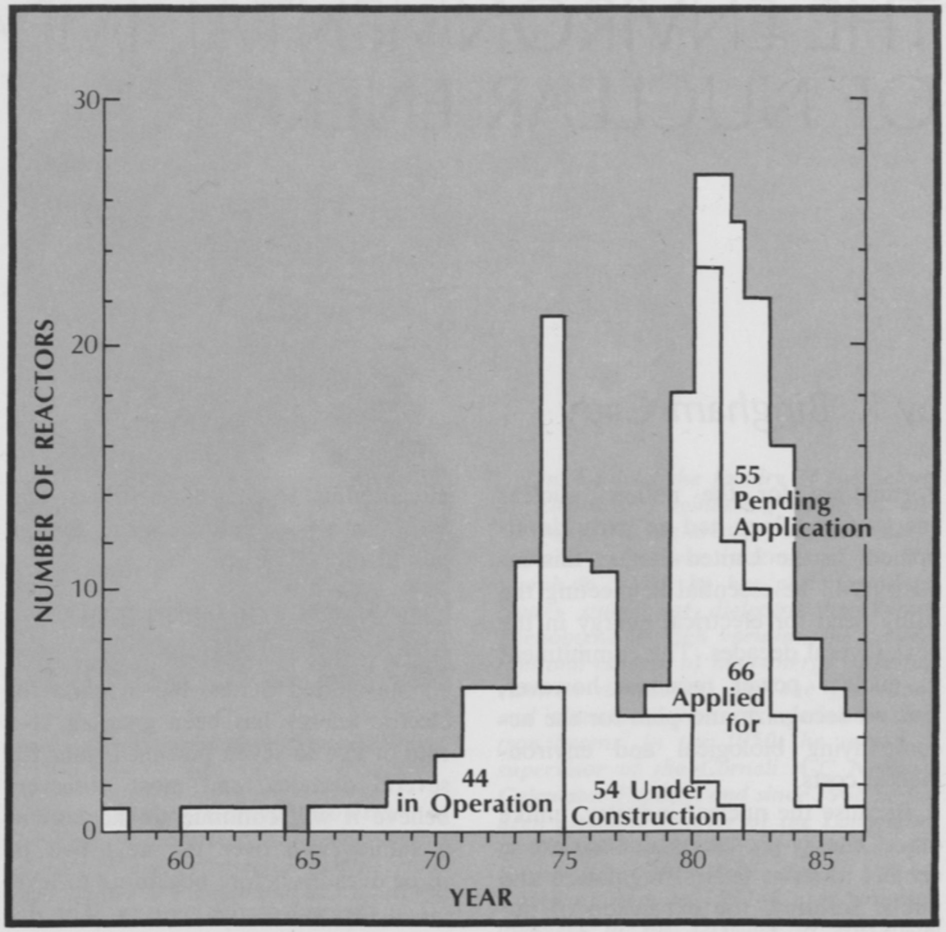


Figure 1. Installation schedule for large nuclear electric power reactors in the United States. Among the 219 reactors shown are 138 pressurized water reactors (PWR) manufactured by Westinghouse (87), Babcock and Wilcox (24), and Combustion Engineering (27); 69 boiling-water reactors (BWR) manufactured by General Electric; and 10 high-temperature graphite reactors (HTGR) manufactured by General Atomic. The coming liquid metal fast breeder reactors (LMFBR) will probably be produced by Westinghouse, General Electric, and Atomics International. Not shown in the figure are several smaller prototype or demonstration reactors, a large number of research reactors (including two at Cornell), and 143 naval propulsion reactors in operation or authorized by the Congress. The naval reactors account for 1,150 reactor years of experience and the civilian power reactors account for an additional 1,000 reactor years of experience (including 23 at Cornell).

sixty-six awaiting construction permits, and fifty-five being planned, for a total of 219.

FUELS AND THEIR BIOLOGICAL AND ENVIRONMENTAL COSTS

Figure 2 shows an estimate of the biological and environmental costs associated with the use of coal, residual oil, and nuclear fuels for the generation of electricity. This illustrates the kinds of costs that are and will be borne by society in addition to the electricity bills paid by consumers.

Associated with the use of coal are air pollution due to sulfur dioxide, soot, and nitrogen oxides; coal-train accidents; environmental damage caused by mine acid; the need for strip-mine reclamation; black-lung disease in miners; and occupational injuries and death resulting from mining operations. Residual oil use entails air pollution at the power plant that is proportional to the sulfur content of the oil; some air pollution at the refinery; damage from oil spills; and occupational injuries and death.

Nuclear fuels have different biological costs, the most important being that associated with the release of krypton-85 during fuel reprocessing. This noble-gas isotope, which has a half-life of 10.7 years, mixes in the atmosphere of the northern hemisphere and is a skin and lung hazard in the United States, Europe, and Asia. The hazard is greatest in Asia because the population is larger there than in the United States or Europe. The radiation dose would be expected to increase in the future because of the growing

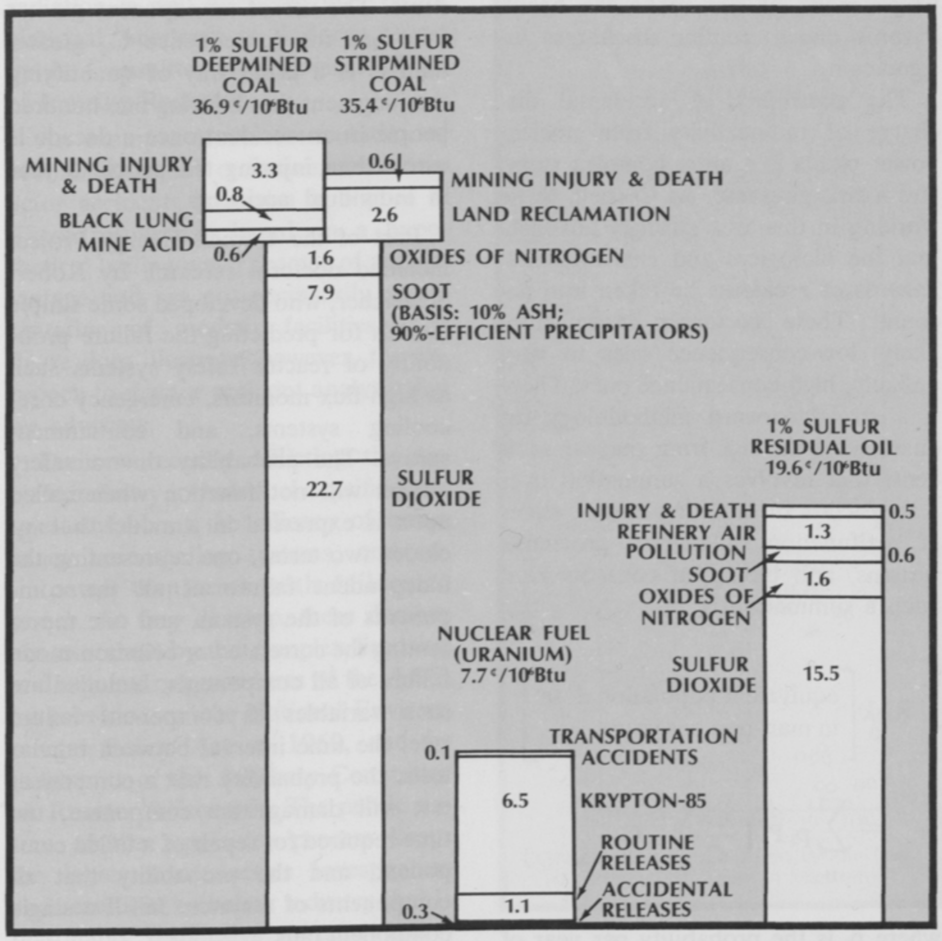


Figure 2. Environmental and health costs associated with various fuels used in generating electricity. These costs are borne by the public and are in addition to the economic cost of fuel paid for by electricity consumers. The numbers are taken from Chaim Braun, Electric Power System Expansion Subject to Internalization of Environmental Costs, *a Ph.D. dissertation in preparation in the Graduate Field of Nuclear Science and Engineering at Cornell. Braun is a member of the research staff of the Cornell Energy Project.*

world population. I think that in the future, krypton-85 releases from United States sources will be controlled by Atomic Energy Commission (AEC) regulations requiring nuclear fuel reprocessing plants to install cryogenic noble-gas strippers and facilities to compress and bottle krypton-85. (The *AEC Rules and Regulations* governing civilian nuclear facilities appear as Title 10 of the *Code of Federal Regulations* and are available for inspection at several libraries and laboratories on the Cornell campus.) Other detrimental effects associated with the use of nuclear energy include routine and accidental radiological discharges from power reactors, lung cancer in uranium miners, and transportation accidents involving spent fuel.

The costs of long-term storage or eventual disposal of high-level wastes from fuel reprocessing plants do not appear in Figure 2 because they were calculated as part of the economic cost of nuclear-power generation. There are several schemes for the eventual storage or disposal of high-level radioactive wastes which appear feasible. A. S. Kubo and D. J. Rose, in an article, "Disposal of Nuclear Wastes," in the December 21, 1973 issue of *Science,* discuss several of these options: (1) disposal in engineered near-surface structures; (2) retrievable deep-rock storage; (3) irretrievable salt-dome disposal; (4) creation of fused glass-rock matrix; (6) disposal in antarctic rocks and ice. Each of these options could be coupled with recycling of the long-lived actinides. Current Atomic Energy Commission regulations require the solidification and shipping of nuclear wastes to federal repositories; bids for the construction of the first such repository, an engineered surface-storage facility, will be solicited this year.

ROUTINE AND ACCIDENTAL RADIOLOGICAL DISCHARGES

As part of the Cornell Energy Project research on national energy needs and environmental quality, several studies of radiological insults from nuclear facilities have been made. These studies include assessments of routine radiological discharges from nuclear reactors and fuel-reprocessing plants, and accidental discharges from reactor plants.

Typical routine gaseous discharges from boiling-water reactors include noble gases (krypton-85m, 85, 87, 88, and xenon-133m, 133, 135), halogens (iodine-131, 132, 133, 135), and some tritium and nitrogen-13. Part 20, *Standards for Protection Against Radiation,* of the *AEC Rules and Regulations,* limits radiation exposure to an individual in the unrestricted area surrounding a nuclear facility to 500 millirem per year, and requires that all radiation exposures be kept "as low as practicable." An appendix to Part 50, *Licensing of Production and Utilization Facilities,* defines "as low as practicable" numerically and requires that releases of noble gases, tritium, and iodine from light-water reactors be reduced to small fractions of the naturally occurring background radiation and the normal radiation exposures from medical and dental x rays. These AEC rules and their analogs for liquid radwaste discharges have resulted in the design and development of augmented radwaste systems in nuclear plants which make or can make the health hazards due to routine discharges insignificant.

The possibility of accidental discharge of radioactivity from nuclear power plants is a more complex story, and a changing one. At Cornell, those working in this area strongly advocate that the biological and environmental hazards of accidents be taken into account. These accidents range from likely, low-consequence ones to very unlikely, high-consequence ones. There is a straightforward methodology for quantifying the risk from nuclear accidents that involves a summation over a large class of initiating events, states of malfunction of reactor protective systems, and biological consequences. Such a summation is:

$$\text{Risk}\left[\begin{array}{l}\text{equivalent population dose}\\ \text{in man-rem per year}\end{array}\right] = \sum_{ij} p_i P_j \left(\frac{C_{ij}}{C}\right)^F C\,,$$

where p_i is the probability per year of an initiating event (for example, blackout, operator error, tornado, earthquake, or steam-line break); P_j is the probability that a consequence-limiting safety system (such as an emergency ventilation system, auxiliary generators, high-flux monitors, or an emergency core-cooling system) will be in a failed state; C_{ij} is the resulting consequence measured by the population dose in man-rem; C is the nominal consequence of a likely accident; and F is an exponent which places a nonlinear risk on high-consequence accidents. The use of an exponent greater than one for consequence C_{ij} greater than C is a usual way of quantifying the judgment that injuring one hundred people in an accident once a decade is worse than injuring ten people a year in individual accidents.

Part of the Cornell Energy Project included doctoral research by Robert Schleicher, who developed some simple models for predicting the failure probability of reactor safety systems such as high-flux monitors, emergency core-cooling systems, and containment sprays. The probability that a safety system will not function when called upon is expressed in a model that includes two terms, one representing the independent failure of all the components of the system, and one representing the correlated or common-mode failure of all components. Included are such variables as component failure rate, the time interval between regular tests, the probability that a component test will damage the component, the time required for repair of a failed component, and the probability that all components of a system fail if a single component fails.

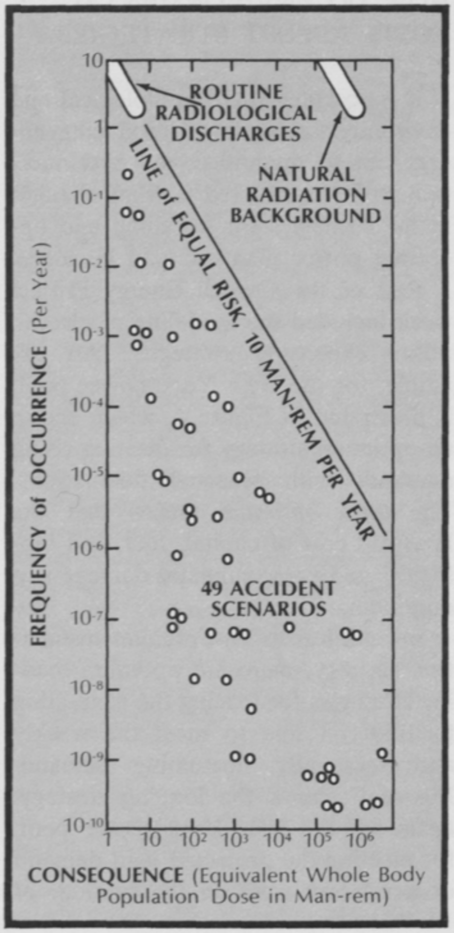
The quantification of failure and accident probabilities, combined with *fault tree analysis,* the methodology for analyzing a system for failure paths, is highly developed in the space program and is being utilized in the nuclear field with increasing emphasis. An important example is a reactor safety study directed by Professor N. C. Rasmussen of the Massachusetts Institute of Technology and sponsored by the AEC and MIT; a report will be published shortly. The quantification of the biological hazards of nuclear radiation is well discussed in a recent National Academy of Sciences report by the Committee on Biological Effects of Ionizing Radiation.

An example of the computation of probabilities and consequences of reactor accidents is shown in Figure 3. These results are based on a hypothetical boiling-water reactor of ancient vintage and are not necessarily representative of modern facilities. The figure does illustrate, however, the approach to reactor accident analysis that we advocate.

Demons recently afflicting the nuclear industry include fuel densification, questions about the efficacy of emergency core-cooling systems, and anticipated transients with failure to scram. As they develop, these demons are exorcised by the complex licensing and regulatory procedures of the AEC, by provisions of the National Environmental Policy Act of 1969, and by judgments of the Advisory Committee on Reactor Safeguards. The public nature of the regulatory process keeps the issues under active investigation and results in a nuclear industry that is reasonably responsive to safety questions.

The attention given to potential hazards is exemplified by recent worries that in the event of a rupture in a cold leg of a pressurized water reactor, steam binding might occur in the steam generators and prevent the emergency core-cooling system from functioning properly. Several resolutions of this potential problem have been proposed:

(1) Demonstration by a combination of experiment, analysis, and operating experience that the systems are adequate.



(2) Installation of internal vent valves in the core barrel, as provided in the Oconee nuclear power plant.

(3) Raising of the steam generators.

(4) Direct injection of emergency core-cooling water into the core instead of into the cold legs of the primary coolant piping; this is done in boiling water reactors and in recent pressurized water reactors used for naval propulsion.

(5) Evolution toward other types of nuclear reactors, such as the high temperature graphite reactor and the liquid metal fast breeder reactor.

Figure 3. Accident probabilities and consequences assumed for a hypothetical boiling-water reactor (BWR). The circles represent 49 accident scenarios, comprising common accidents such as spontaneous fuel pin failure, less likely fuel-handling accidents, and very unlikely ruptures of the double containment system. The BWR is assumed to be situated in a region which has a population of two million people living within 50 miles of the plant. In this representation, consequence is measured as population dose in man-rem pertaining to the population of two million (rem is a unit of radiation dosage, biologically equivalent to one roentgen of radiation).

The risk associated with accidents from this one nuclear plant is shown as comparable to the risk associated with the routine radiological discharges from the same reactor, and small compared to the risk from the natural radiation background (which is taken to be about 300,000 man-rem per year in a population of two million).

Calculations based on an interpretation that 3,400 man-rem causes one malignancy or genetic injury indicate that over a 40-year period the population of two million persons could expect about 3,500 malignancies or genetic injuries caused by natural radiation and less than one caused by the nuclear power plant. In this same population over the same time period, there would be about 20,000 automobile deaths, 130,000 deaths caused by all types of malignancies, and 400,000 deaths from cardiovascular disease.

The probabilities and consequences depicted are taken from the Ph.D. work of Robert W. Schleicher, Jr., in the Graduate Field of Nuclear Science and Engineering at Cornell. Schleicher's dissertation, Stochastic Decision Making Applied to Nuclear Reactor Safety, *was submitted in August 1972.*

HOW DO ENVIRONMENTAL COSTS AFFECT STRATEGIES?

If it is accepted that the biological and environmental costs of producing energy can be quantified, the next question to be considered is what changes in the strategies for installing and operating power plants should be made.

Part of the Cornell Energy Project work included the modeling of electric utility expansion strategies. An example, for the New York power pool, is illustrated in Figure 4, which shows an optimum strategy for meeting rising demands with seasonal fluctuations. The term *optimum* means that the levelized cost of capital, fuel, and biological and environmental damage is a minimum.

In addition to an optimum installation strategy, there are optimum loading strategies for placing the generating facilities on line to meet the weekly and seasonally fluctuating demand. Figure 5 shows the loading strategy, again for the New York power pool, for meeting the projected load demand of a selected week in the summer of 1985. The hydroelectric facilities are first base-loaded to their seasonal capacity. Next the nuclear plants with the lowest fuel cost are placed on line; unused capacity during low-demand periods at night and over the weekend is utilized to fill the pumped storage ponds. The intermediate-sized coal and oil plants are loaded next, in an order determined by the relative fuel costs and the associated biological and environmental costs. Finally, the peak demand during the weekdays is met with use of gas-turbine peaking units burning high-cost distillate fuel oil.

Figure 6 shows an example of the levelized costs of producing electrical power in the New York power pool with use of a "commercial optimization" and "societal optimization." The commercial optimization employs an installation and operation strategy that results in the lowest direct capital and fuel costs, without consideration of biological or environmental costs. The societal optimization uses a strategy that results in minimum total costs, including those of biological and environmental insults. It can be seen that

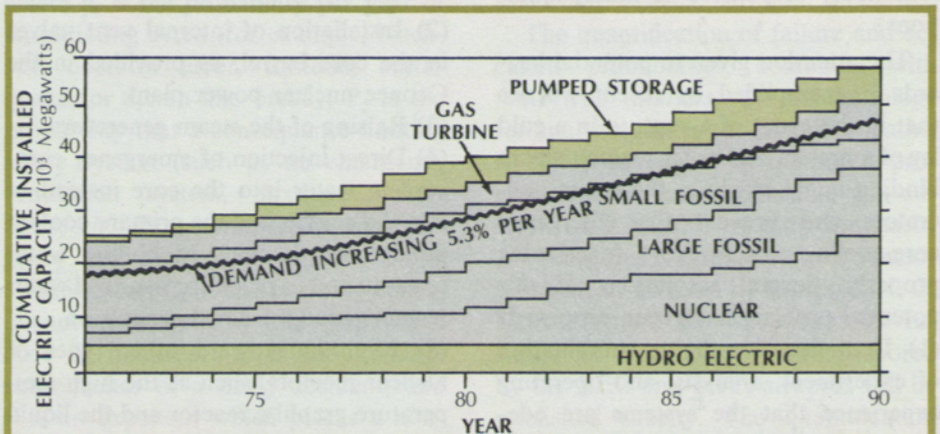


Figure 4. An expansion strategy for the New York power pool. The cumulative installed capacity is shown as it existed through 1973; as it will be extended in the years up to 1980 by present commitments, and as it is predicted to be through the 1980s on the basis of an "optimum" strategy. Demand is assumed to rise at 5.3% per year from 1974 through 1989 and to have seasonal fluctuation peaks in summer and winter. The installation strategy calls for increasing pumped storage and gas-turbine peaking capacity, used to meet daily and seasonal peaks. The "small fossil" category includes most existing coal and oil plants; their capacity will decrease as they are retired from service because of age, inefficiency, and environmental pressures. The "large fossil" and "nuclear" categories will grow to meet the increasing demand for electricity. Hydroelectric plant capacity is depicted as unchanging because of the assumption that no more available sites exist in New York State. The data for Figures 4, 5, and 6 are based on the work of Chaim Braun, a member of the Cornell Energy Project staff.

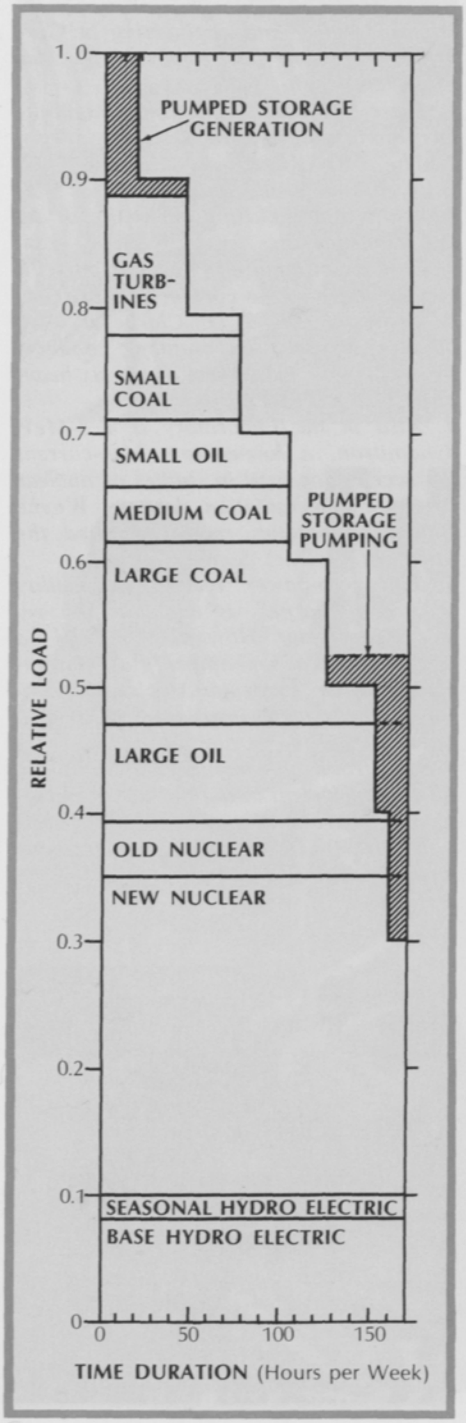
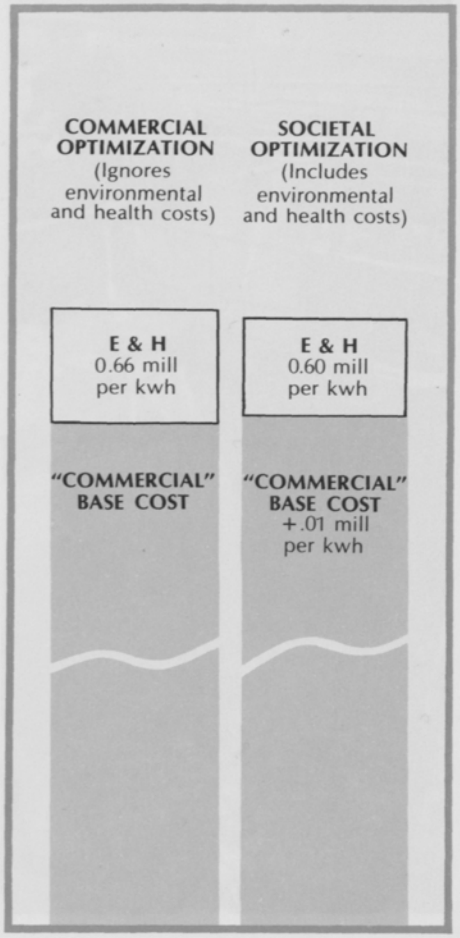


Figure 5 (left). An optimum loading strategy for the New York power pool for a summer week in 1985. The loading sequence proceeds from bottom to top. The optimum loading strategy for any week depends on variations in demand, on the plants available for generation, and on relative total operating costs, including fuel costs and environmental and health costs. The large coal, large oil, and nuclear plants are used to generate electricity to pump water during the nighttime and on weekends. This pumped storage is then used to regenerate electricity during the daytime demand peaks. Additional demand during peak hours in summer and winter is satisfied by the use of gas turbines. If environmental costs were not taken in account, the large coal plants would be loaded ahead of the large oil plants because of the lower cost of coal as a fuel; the savings would be more than offset, however, by increased environmental costs due to the associated air pollution. It has been assumed that oil containing 0.5% sulfur is used in the large oil plants and that coal of 3% sulfur content is used in the large coal plants. The large coal plants are assumed to be fitted with equipment for 70%-efficient removal of sulfur dioxide from stack gas.

Figure 6 (right). Comparison of the costs of electricity depending on whether or not the optimization scheme takes environmental and health costs into account. The case shown is for the New York power pool. A "commercial optimization," which ignores environmental and health costs, results in a levelized base cost that is slightly less than the comparable cost derived by a "societal optimization," which includes environmental and health costs in formulating the installation and loading strategies. However, when the environmental and health costs are added to the base-cost figures, the comparison shifts in favor of the "societal optimization:" the difference in environmental and health costs (0.06 mill per kwh) more than offsets the difference in base costs (0.01 mill per kwh).



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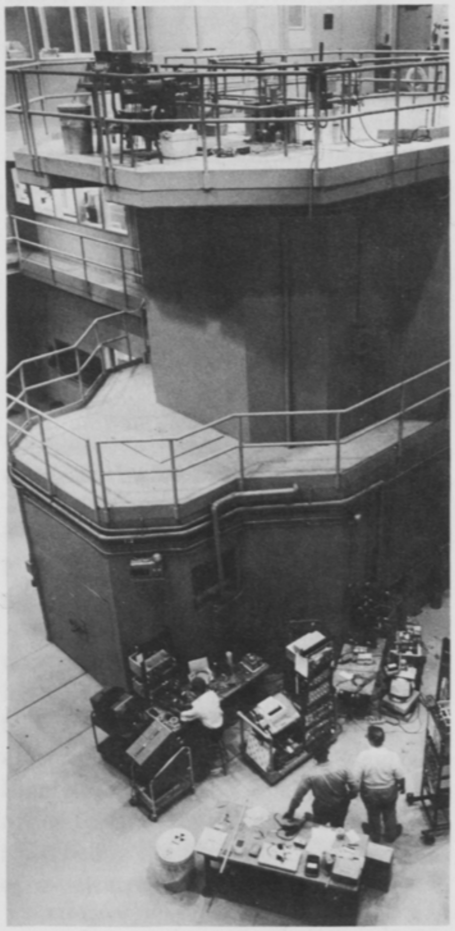

A center for research and instruction in nuclear science and engineering at Cornell is the Ward Laboratory of Nuclear Engineering.

1. Safety precautions include continuous monitoring of radioactivity levels.
2. The TRIGA reactor, a research facility, has a steady-state power of 100 kilowatts and a pulsing capability of up to 250 megawatts.
3. Professor Cady looks down through 25 feet of water at the core of the TRIGA.
4. Professor David D. Clark (at left), director of the Laboratory, conducts experimental work at one of the six beam ports of the TRIGA.
5. Also in the Laboratory is a 3-MeV dynamitron, a low-energy, high-current ion accelerator used in studies of nuclear structure and radiation damage. Wayne Rial, the operator, recently earned the M.Eng. (Nuclear) degree.
6. The zero-power reactor, a facility unique to Cornell, is explained by reactor supervisor Howard Aderhold to members of a sophomore class in nuclear science. Professor Vaclav O. Kostroun, the course instructor, is at left.
7. Inspecting the zero-power reactor core are Kostroun and members of the class.
8. An experiment in the nuclear measurements laboratory is set up by Robert Fairchild, Ph.D. candidate and teaching assistant.

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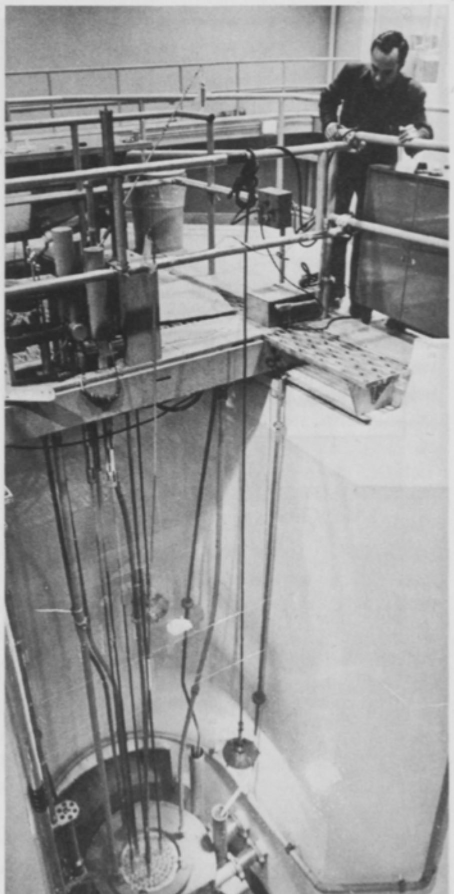

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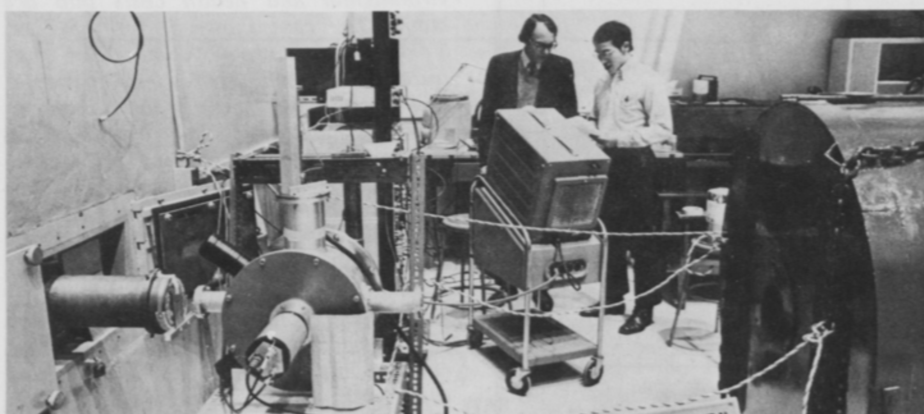

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"... the outlook for nuclear energy is extremely good when its costs and hazards are compared with others associated with the long-term energy problem."

the optimization process would effect a reduction in total cost per kwh. This would be accomplished by installing several more nuclear plants instead of coal plants and reordering the loading strategy in such a way that oil plants are loaded before those coal plants which do not have stack-gas cleanup systems to reduce the emission of sulfur dioxide. The saving of 0.05 mill per kilowatt hour is small compared to the base cost of production (around 14 mills per kwh) but it is assured and it has a present worth of $150 million.

NUCLEAR SCIENCE AND ENGINEERING AT CORNELL

Some of the problems in nuclear environmental engineering that are being investigated at Cornell by staff members and students associated with the Cornell Energy Project have been discussed. In addition, current research projects in nuclear engineering at the University include studies of reactor-plant transients in liquid metal fast breeder reactors. Research in nuclear science, which provides a base for much of the teaching in the nuclear area at Cornell, includes a program in nuclear isomeric fission directed by Professor David D. Clark, and studies in atomic and nuclear structure physics under the leadership of Professor Vaclav O. Kostroun. The Ward Laboratory of Nuclear Engineering is the center for much of this teaching and research.

The Master of Science and Doctor of Philosophy degree programs in nuclear science and engineering have provided researchers to the industry, the national laboratories, and universities. Cornell Ph.D. graduates, for example, have become faculty members at MIT, the University of Texas, the University of Missouri, Clarkson College, Catholic University, Quincy College, the University of Delhi, and the University of the Negev.

Of the various graduate programs in this area that are available at Cornell, one that is particularly pertinent to matters of nuclear reactor safety is the Master of Engineering (Nuclear) degree program. Students who have made an appropriate selection of elective subjects at the undergraduate level may enter this program after receipt of a baccalaureate degree in any engineering discipline. The graduates of the professional program enter the nuclear industry in many places; they work for architect-engineers, constructors, reactor designers and manufacturers, governmental regulatory agencies, and the government-owned national laboratories, which have made important contributions to the development of safe and economical nuclear energy in the United States.

We believe that Cornell is accepting its share of the special responsibility the universities have in the overall national effort to meet the urgent need for expansion of energy-production capacity, especially nuclear reactors and related facilities. The nation will depend on the universities to educate nuclear and environmental engineers and scientists who are prepared to carry out the necessary research and development efforts, and to build, operate, and regulate the current light-water reactors, the coming advanced converters and breeder reactors, and in the long-term future, thermonuclear fusion reactors.

Professor Cady discusses a design project for the M.Eng. (Nuclear) degree program with student Robert Dunki-Jacobs.

K. Bingham Cady, associate professor of applied physics, is a specialist in nuclear reactor physics and nuclear engineering. In recent years, problems of reactor safety and associated problems of environmental and health protection have been areas of special interest to him, and he heads Cornell's Master of Engineering (Nuclear) degree program, which emphasizes these aspects of nuclear engineering education.

Cady came to Cornell in 1962 after completing doctoral studies in nuclear engineering at the Massachusetts Institute of Technology (MIT). His undergraduate degree, in naval architecture and marine engineering, was awarded in 1956 by MIT.

He received his first professional experience in nuclear engineering at the Shipbuilding Division of the Bethlehem Steel Company. While he was a graduate student, he worked part-time for the consulting firm of Jackson and Moreland, Inc., on studies of nuclear systems engineering, radiation shielding, and power generation economics.

During a leave from Cornell in 1966, he worked at the Knolls Atomic Power Laboratory of the General Electric Company. In 1969–70 he spent a leave at the Atomic Energy Commission, working in the Division of Reactor Licensing on the evaluation of safety analysis reports submitted in support of operating license applications for nuclear power plants.

At the University, he participates in the Cornell Energy Project, mentioned in his article, which sponsors much of the research he supervises. He has been active also in a number of University and College affairs. At the present time he is a member of the Graduate Professional Programs Committee and the Core Curriculum Committee of the College of Engineering, faculty adviser to Tau Beta Pi, a member of the University Faculty Review and Procedures Committee, and a member of the Faculty Council of Representatives.

Cady is a member of the American Nuclear Society, and a founding member and past chairman of the organization's Niagara-Finger Lakes Section. He is a member also of the honorary societies Phi Eta Sigma, Tau Beta Pi, and Sigma Xi.

COMMENTARY

Cornell Lectures on Energy Policy

A spectrum of opinions was presented in a College of Engineering spring-term weekly lecture series on Energy Policy: Issues and Options, in which experts in various aspects of energy supply and management came to the campus as participants.

The University's Program on Science, Technology, and Society cosponsored the series with the College of Engineering, and some of the lectures were sponsored also by the University Lecture Committee.

Organizer for the series was Peter L. Auer (at right), professor of mechanical and aerospace engineering and director of the Laboratory of Plasma Studies.

■ An overall view of the current shortage situation—"how we got here and how we are going to get out"—was offered by the first speaker, Harry Perry, a consultant for Resources for the Future, who has had extensive experience on the national level in energy policy areas, especially those concerned with the coal resource. (Perry was a member of the Cornell Workshop on the Fossil Fuel Option—see page 6.)

Among the "complex and varied" reasons he cited for current shortages are, besides the recent oil embargo, decreased drilling for natural gas, declining coal production, slowness of development of the nation's nuclear capacity, and an exponential increase in demand. Blame for the situation, he said, has been variously placed on consumers; on environmentalists for contributing to delays in nuclear plant construction and to restrictions on coal mining and oil drilling, etc.; on the profit structure of corporations; and on lack of governmental leadership.

Alleviation of present shortages, Perry pointed out, can be brought about most quickly by decreasing consumption—in "small but painless" conservation measures, in more costly but nondisruptive ways, or, most effectively, in restrictive economic actions that would affect life styles. There is less flexibility in the alternative of increasing supply, he indicated. In the short term, some temporary "cutting of corners" on environmental restrictions will be needed, along with conservation efforts and increases in production. For the medium term, three to five years from now, more could be done, but decisions must be made now so that policy is understood. Nuclear plant licensing, for example, should be expedited, and a decision should be made on whether to undertake the exploitation of shale oil on a large scale. An overall R and D policy is needed to promote the development of new technologies or better utilize older ones, he said. In the long

Perry

Decisions must be made now so that national policy is understood.—Harry Perry

Fisher

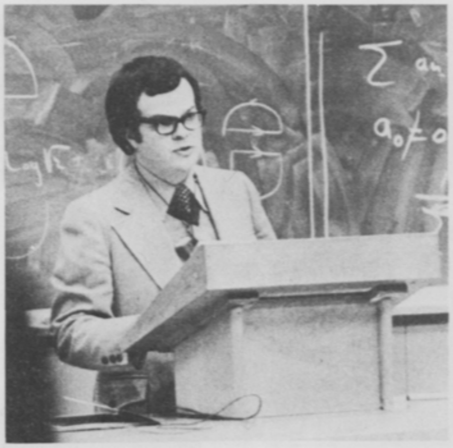
We have enough fossil fuel for five hundred years.—John C. Fisher

range, the most crucial need is for an R and D program to develop new fuel sources. He predicted that the era in which oil and gas will be used in large quantities will end around 1990.

■ A somewhat different view was presented by the following speaker, John C. Fisher, manager of energy systems planning for the power generation division of the General Electric Company, who estimated that the United States has twice as much fuel in *reserves* of coal, petroleum, gas, and shale oil as will be needed by the year 2000. On the basis of estimated *resources,* which include submarginal and undiscovered sources, he concluded that the nation has enough fossil fuel to last five hundred years. Other sources, notably nuclear energy, would provide enough energy for a million years, he said. Economic and possible environmental limitations were not included in these estimates. An important point, he said, is that "the pace at which a shift to nonfossil sources occurs does not have to be dictated by oil supply." According to his analysis, a plateau in the price of crude has been reached; after some fluctuation, prices will again rise because of depletion. Eventually, synthetic liquid fuels manufactured from coal might once again bring prices down.

Fisher also offered an explanation for the unexpectedly rapid rise in consumption that has occurred over the past ten years. He pointed out that about 73% of energy consumption in the United States is job-related, and suggested that the increase in numbers

Wilson



The petroleum industry is not truly competitive.—John W. Wilson

of women in the work force can explain the higher-than-expected increase in demand, which should level off in ten to fifteen years. Greater employment of women is therefore one of the causes of the current shortage; another is the environmental movement, which has created a need for additional energy use, delayed the building of nuclear plants, and forced a shift to refined fuels that has taxed refinery capacity. He predicted that the shortage would be over soon, as productive capacity catches up with demand.

■ The lack of true competition in the petroleum industry was cited as a major factor in the energy crisis by John W. Wilson, an independent economic consultant and former chief of the division of economic studies at the Federal Power Commission. The petroleum industry also owns large shares of the coal and nuclear fuel reserves, he said, and controls 75 percent of the nation's energy output. He described a network of ties among the major oil companies, existing as joint ventures such as bidding combines, which agree to rotate bids on, for example, federal offshore oil fields; interlocks among banks and petroleum companies; transportation networks, such as pipelines; and frequent joint ventures in production, including interlocking lease ownership arrangements. Combines also control the international oil market, he said.

A close working relationship among major companies is not good for the free market system and will not be effective in solving the energy crisis, Wilson said; future policy decisions should be made in the public rather than the industrial interest. Alternatives he outlined include the elimination of intrastate exemptions from price regulation, the establishment of an independent public petroleum corporation similar to the TVA, and the enactment of antitrust statutes.

Wilson emphasized that such measures would require strong public and political support, which is dependent in turn on better public understanding of the underlying causes of the energy crisis. Without informed opinion, he said, the oil industry "will continue to be a vehicle for private gain."

■ Aspects of the nuclear power industry, the only utility that is federally licensed and regulated, were discussed by Roger Boyd, assistant deputy director for reactor projects in the Division of Licensing of the Atomic Energy Commission.

Radiological safety is a primary concern in the mandatory review required for licensing, he said; environmental protection and antitrust considerations are also important. He pointed out that decisions on safety and environmental issues are "mostly a matter of judgment." The nuclear industry is the only one legally required to provide a forum for public participation in the decision-making process.

As experience has accumulated in the industry and the regulatory agency, Boyd said, the level of technical sophistication in safeguards has increased. Time is a crucial factor in the development of nuclear capacity, however, and an essential aim is to provide "better and faster" review and implementation. Since questions about safety—such as the possibility and consequences of a core-cooling accident or the possible hazards of radioactive effluents under normal operating conditions—cannot be answered quantitatively, the general objective is to provide the best possible engineering.

The time required for the process of planning, authorizing, and building a nuclear power plant, Boyd said, is now about ten years—too long in view of the nation's urgent need for this energy source. Several ways of reducing this time are being implemented: site approval in advance of plant design approval, and a tightening of Commission procedures, including more use of standardization in plant design.

Boyd

Public participation in nuclear power policy decisions is assured by law.—Roger Boyd

Petroleum's share in the energy supply mix will decline after 1980.—Russell L. Nielsen

Nielsen

■ A mix of energy sources to replace major reliance on oil will be needed in the near future. This view was expressed by Russell L. Nielsen, an adviser in the planning department of Exxon Corporation, in the fifth lecture of the series. Of the world's fossil fuel resources, coal is in largest supply, he said, and is "destined to again become the principal energy source." The share of petroleum in the mix will decline after about 1980, he predicted.

The production of crude oil is limited physically by the discovery rate, Nielsen said, as well as practically by governmental policy. In order to satisfy increasing demand, there would have to be a dramatic jump in the discovery rate, but actually "we seem to have reached a crossover point; production is now proceeding faster than discovery. Just how abruptly the discovery rate will decline as the ultimate limit in resources is approached is unknown, he said. Crude oil prices are expected to decline from the current peaks, but continue to show an overall gradual rise. Eventually, oil made by coal liquefaction will dominate the market.

Of available alternatives at the present time, he said he favors a policy of maintaining a high rate of economic growth with institution of conservation measures which could moderate, though not stop, the growth of energy demand. Increases in oil imports will be needed for the immediate future, and the development of alternate energy sources for the long range should be started. These would include, in addition to coal, supplemental sources such as shale oil and geothermal energy; nuclear energy; and some solar energy.

■ Geothermal and solar energy offer important alternatives for energy supply as the earth's fossil fuels are depleted. This view was advanced by Paul Craig of the Office of Energy Research and Development Policy of the National Science Foundation (NSF), which has special responsibility for these areas of the national R and D energy program.

Geothermal energy is a practical reality in many parts of the world, he said, and in the United States, particularly in the west, recent leases indicate that industry will enter the technology in a major way. The most promising geothermal source for massive production of energy is the extraction of heat from hot rocks, and Craig discussed several schemes for accomplishing this. He estimated that as a resource, the potential of hot rocks is comparable to that of coal in the United States. Solar energy, a nondepletable resource, can be utilized in several ways, including the production of electricity from solar radiation. The cost of solar energy is becoming more attractive, Craig said, as technology brings the price down and the cost of other forms goes up. The NSF is now experimenting with solar heating of public buildings.

Craig considered the broad problem of energy supply in terms of conservation, new sources, and environmental effects. He contended that the United States must "get off the exponential curve" of increasing energy demand, and that a lower per capita consumption and lower gross national product would not necessarily lower the standard of living. Environmental as well

Major changes in our ways of addressing the complex problems of energy use will be required in thirty to fifty years.—Paul Craig

Our society must come to grips with problems of resources, one of which is energy.—Douglas C. Bauer

Craig

as institutional problems will increase along with energy use, he said, and new ways of addressing the exceedingly complex issues are required. "The decision-making machinery is not working very well in this society," he said. "The best interests of all are not necessarily achieved by the practice of everyone seeking his own best interests."

■ Conservation measures in the immediate future and basic changes in the long range are essential for solution of the nation's energy and other resources problems, according to visiting lecturer Douglas C. Bauer, deputy assistant director of the Office of Energy Conservation, Department of the Interior and Federal Energy Office. The lifting of the oil embargo can have only a minimal effect on the overall situation, he said.

Bauer illustrated the need for new patterns in energy use with data on changes in the energy required per passenger mile by various modes of transportation. Current trends favor the use of vehicles with high and increasing energy intensity, such as advanced aircraft and automobiles for urban driving. On the other hand, railroads, which have exhibited a declining energy intensity, are in economic trouble. "We must turn around some very well developed trends," Bauer said.

In reviewing the possibilities for achieving Project Independence, the government's goal of national self-sufficiency in energy, Bauer pointed out some difficulties in formulating plans. These include a lack of accurate and independent information on available fuel supplies, uncertainty about economic factors such as oil prices in the future, and unknown variables, including how the public will respond to recommended conservation measures and innovations such as solar heating for homes. In addition, he said, there is an apparent inability of federal government and its bureaucracy to take the really "long view" in making and changing policy.

Better understanding of the qualitative and quantitative costs of national energy independence, and ways of assessing "tradeoffs" are needed, and will require the consideration and participation of the nation's various institutions and the people as a whole. "We must proceed," Bauer said, "from a sense of the kind of society we want to live in and pass on to future generations."

■ Bauer's talk was the last of the series prior to spring vacation. Speakers scheduled for the remainder of the term included Stanley M. Greenfield, assistant administrator of the Environmental Protection Agency, and Louis H. Roddis, Jr., vice chairman of the Board of Consolidated Edison of New York.

REGISTER

A Man and a School

The stories of William R. Sears and aerospace engineering at Cornell are inseparable. Sears founded the Graduate School of Aeronautical Engineering and served as its director for many years. He saw it develop into the Graduate School of Aerospace Engineering with the advent of a new dimension to aircraft flight, and then, two years ago, join with a related discipline to form the Sibley School of Mechanical and Aerospace Engineering. This spring Sears will conclude a twenty-eight year record of leadership in engineering and applied mathematics at Cornell.

Bill Sears came to Cornell in 1946 at the invitation of engineering dean S. C. Hollister, who shared Sears' enthusiasm for initiating a graduate program in aeronautical engineering. As Edwin L. Resler, Jr., present director of the Sibley School, points out, Sears "built the aeronautics school from the ground up." He planned the program and hired the faculty, which soon developed into an assembly of some of the most prominent men in the field: Arthur Kantrowitz, John M. Wild, Nicholas Rott, and Y. H. Kuo.

As a tribute to William R. Sears, the College of Engineering is publishing a volume of his collected papers. The editor is Nelson H. Kemp, left, of the Avco Everett Research Laboratory, who worked under Sears for a Ph.D. degree granted in 1953.

The College also honored Sears with an Engineering Award, a form of recognition initiated during the College Centennial in 1971. The bronze medal, inscribed "in recognition of his service to the College," was presented during a dinner in Sears' honor on May 11 in Ithaca. More than one hundred aerospace alumni attended the dinner.

Physically, the beginnings were modest: the first laboratories and classrooms were set up in an old frame annex behind Franklin Hall. Subsequent housing in Temporary Building I, a converted World War II barracks set up along Forest Home Drive, was more spacious and offered the advantages of flexibility: when more space was needed for, say, a wind tunnel, it was easy to just knock down a wall and make room. By 1959 Grumman Hall, especially designed for aerospace engineering, was completed on the Engineering Quadrangle, and the School moved in—with some trepidation. There was a feeling, Sears explains, that the excellence of the School, flourishing in makeshift quarters, might somehow be compromised in more elegant surroundings. It survived the transition, however, and continued to develop.

Over the years, the reputations of the School and of William R. Sears grew together. Sears has received many honors from national science and engineering academies and societies, including the Bendix Medal of the

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At Cornell Bill Sears is known for his wide-ranging nonprofessional interests as well as for his academic and professional leadership.

1. Bill Sears uses his own airplane, a Twin Comanche, to meet professional engagements around the country. Frequently he is accompanied by his wife, Mabel. Shown with Sears in this 1967 photograph are Mrs. Sears, at center, and Toni Anthony, who became his secretary soon after his arrival at Cornell and is now the administrative assistant in the Sibley School.

Sears, who is licensed for instrument flying, finds that his own transportation is sometimes more reliable than commercial flights: because he has a single destination, he needs to be concerned with weather conditions over a restricted geographical area only.

2. Scuba diving and underwater photography is a recently acquired hobby of the Searses. Bill, at right, is shown with a professional diver at Cabo San Lucas. Places where Sears has gone scuba diving include the Bahamas, Key Largo, Baja California, and Santa Catalina Island. Last December he attended an international meeting in Israel and included in the trip some diving in the Gulf of Eilat.

3. Bill Sears, left, regularly plays squash on the University courts; his companion here is Efraim Racker, the Albert Einstein Professor of Biochemistry. (Photo by Roger Archibald.)

4. Since the 1940s Bill Sears has been playing recorders regularly with a local group, which for many years has included M. H. Abrams, at center, professor of English at Cornell, and Jerrold Meinwald, at right, Cornell professor of chemistry. The group is shown during a recent Sunday evening session at Abrams' home. The ensemble used to play Elizabethan music every year for students in Abrams' survey course in English literature. It has played also for local groups such as the Friends of Music and has given public concerts on the campus.

American Society for Engineering Education, and election as a Fellow of the American Institute of Aeronautics and Astronautics (AIAA), a Fellow of the American Academy of Arts and Sciences, and a member of the National Academy of Engineering and the National Academy of Sciences. He was selected as the von Kármán Lecturer of the AIAA, as Lecturer in Aeronautics of the Israel Society of Aeronautical Engineering, and as Lanchester Memorial Lecturer of the Royal Aeronautical Society of Great Britain. In addition to publishing many research papers, he has edited two professional periodicals. He has served as consultant to industrial and governmental organizations, and as a member of numerous national advisory groups. At Cornell he has held the John LaPorte Given Professorship since 1962, and was an instigator and the first director of the Center for Applied Mathematics. And, throughout his years at Cornell, he has seen scores of graduates of the aeronautics and areospace engineering program assume positions of responsibility around the world. "The Cornell school made a first-class reputation," he says, "by virtue of the excellence of its faculty and students."

An insistence on excellence is combined, in Bill Sears, with vitality, breadth of interests, a spirit of adventure, and enjoyment of everything he does. These qualities help explain why, at a time of life when many would be seeking to slow down a little and enjoy the pleasures of recognized achievement, Sears is looking forward to a new professional venture this fall, when he will join the University of Arizona faculty. "A new outlook and

Edwin L. Resler, Jr., left, director of the Sibley School of Mechanical and Aerospace Engineering, was one of Bill Sears' Ph.D. students. The picture was taken during the 1971 Engineering Convocation at a dinner for aerospace alumni. Other Cornell faculty members who were students of Sears are Franklin K. Moore, A. Richard Seebass, and Donald L. Turcotte.

environment is good for persons of my age," he comments. "I like the west, the climate of Arizona, the city of Tucson, and the vigor of the engineering faculty. The main drawback is that the university has no squash courts."

Indeed, if one asks about the twenty-eight years he has spent at Cornell, Sears is likely to talk about squash as readily as about aeronautics. He might begin the conversation with mention of his airplane, branch out to his recently acquired hobby of scuba diving, add a few remarks about the musical ensemble he has been playing with since the 1940s, reminisce a bit about his long association with colleagues in fields as diverse as chemistry and English literature, and finally settle down to a consideration of his primary work in teaching, administration, and research.

Sears has been flying since his pre-World War II days at the California Institute of Technology. After earning a baccalaureate degree at the University of Minnesota in 1934, he studied at Cal Tech for a Ph.D. in aeronautics, awarded in 1938, and remained there for several years as an instructor and assistant professor. As part of his duties, he administered and helped teach a civilian pilot training program, and decided to undergo the actual flight instruction along with the students. The interest in flying continued during his subsequent five wartime years as chief of aerodynamics and flight test for Northrop Aircraft, when he was engaged in the design of combat planes such as the Flying Wing and the Black Widow. After he joined the Cornell faculty, Sears discovered that he could combine his love of flying with his need for transportation, and for many years he has been flying himself to conferences and speaking engagements around the country.

His first plane was a single-seat 65-horsepower Mooney Mite that got 30 miles per gallon and was flown by Visual Flight Rules requiring some "occult arts" such as predicting weather conditions over the expected route. Sears keeps a model of the Mooney Mite on his desk. About ten years ago, he took lessons at the Ithaca airport and qualified for an instrument rating on a multiengine plane ("that license was harder to get than a doctorate") and now he flies a Twin Comanche, completely equipped for instrument flying. One of the satisfactions of flying, especially for people with a technical inclination, Sears feels, is in performing a highly technical skill at a professional level. One of the thrills, especially of instrument flying, is "being up over the weather, on top of a great white cloud bank, with only blue sky and sunshine as far as one can see."

Sears' love of flying is shared by his daughter, Susan, a social worker in Indianapolis, who also owns her own plane. A son, David, a Cornell Ph.D. in city and regional planning now on the University of Massachusetts faculty, also took some lessons, during his high-school days, as a member of Cornell's Grad Aero School Pilots, a club that owned and operated its own plane.

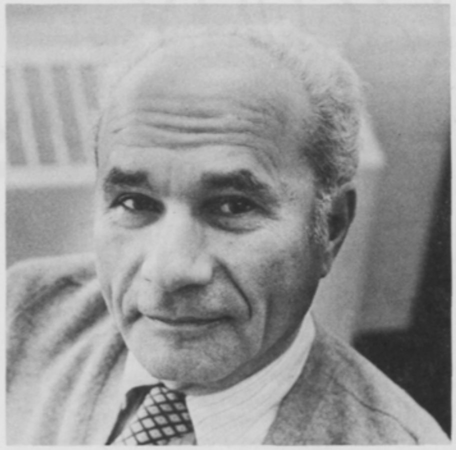
In reflecting on his experiences at Cornell, Sears concludes that one of the great things about the University is the contacts an individual can have with others outside his discipline. "There are always barriers between different groups of people at a university," he says, "but at Cornell they are easy to overcome." Over the years, Sears has participated in such informal interdisciplinary groups as the Research Club, Sigma Xi, and The Circle, whose members take turns discussing their research or special interests in terms understandable to nonspecialists.

His current research is in three areas of aeronautics. In the area of aerodynamic noise, he has studied air-flow phenomena at conditions, such as supersonic flight, for which simple theories are insufficient. He has found, for example, that high rates of acceleration, rather than high velocity, are responsible for significant amounts of aerodynamic noise. A second area of research is concerned with the mostly undesirable effects that occur when the boundary layer of air flowing past an object such as an aircraft wing does not follow the surface, but "separates." Using computer techniques, Sears has been able to calculate boundary-layer separation under unsteady flow conditions. He is perhaps most excited about a third project, the development, in cooperation with Calspan, Inc., of a new wind tunnel that is able to correct for boundary interferences that occur in near-sonic flight, and thereby greatly improve the simulation of real flight conditions.

Research is, of course, central to the graduate program in aerospace engineering, and Sears feels that Cornell has a valuable and rare means of coordinating efforts so that professors and students perform as a professional group and there is a spirit of mutual respect and confidence.

On the broader scale of engineering as a profession, Sears believes that in order for the skills of engineers to be effective at all, there must exist a well developed interface between society and its technical experts. "Our students who are concerned about the 'relevance' of engineering in helping to solve contemporary problems—pollution, urban problems, energy supply, etc.—must recognize that such an interface must exist in order that there be any jobs—any money—to enable engineers to attack these pressing problems," he comments, "and they will have to be patient, for it takes a long time and a lot of experience to bring about this kind of interface. Engineers have been effective in creating weapons and space systems, for example, because the government had literally hundreds of years of experience in setting up an interface in these areas."

The effectiveness of engineers, Bill Sears concludes from the vantage of more than forty years of involvement in engineering, rests on their ability to function as a community of experts who understand how to apply their special skills.



Geophysicist Joins Faculty

Sidney Kaufman, a Cornell-educated geophysicist who spent thirty-seven years with the Shell Development Company, joined the faculty as professor of geological sciences in January.

A specialist in oil exploration and production and in geothermal energy sources, Kaufman is offering a new course in geophysical prospecting. He will also have an important role in Cornell's activities in the Geodynamics Project, a program of research on the dynamics and dynamic history of the earth, in which forty-nine nations are participating.

According to Jack E. Oliver, chairman of the Department of Geological Sciences, Kaufman's appointment will strengthen a developing program in geophysics at Cornell. Both teaching and basic research in this area will be complemented by the contributions of a scientist with extensive industrial experience, Oliver said.

At the time of his retirement from Shell, Kaufman was serving as senior staff research physicist and assistant to the vice president for exploration and production research. He began his career with Shell in 1936, working initially as head of a field crew prospecting for oil. In the late 1930's, in the course of these prospecting efforts, he supervised the first offshore seismic exploration crew in the world. During World War II, Kaufman served with the U.S. Navy as a specialist in radio and radar techniques, and subsequently drew on this experience after his return to Shell as geophysicist and senior staff research physicist. In recent years, in connection with his activities in exploration and production research, he has participated in national panels on energy resources and demand.

The Geodynamics Project work at Cornell, in which Kaufman is involved, will be concerned with one of six high-priority projects outlined for the United States effort by a special National Academy of Sciences committee. This project, to be carried out by representatives of a group of universities, is a study of the fine structure of the earth's lower crust and upper mantle at selected sites in North America. The work is expected to complement seismic studies, already underway at Cornell, on deep mantle structure. It is anticipated that industrial companies will cooperate by extending the measurements of their oil exploration crews to greater depths than they normally investigate, and making the data available for the Project study.

Kaufman received the A.B. degree in physics from Cornell in 1930 and the Ph.D., also in physics, in 1934. He continued at Cornell as a Coffin Foundation Fellow before beginning his industrial career.

He is now serving as an associate editor of *Geophysics,* a director of the Geothermal Resources Council, and a member of the advisory council for the Institute of Geophysics and Planetary Physics of the University of California, the Geophysics Panel of the Air Force Office of Scientific Research, the joint panel of the Committees on Seismology and Rock Mechanics of the National Academy of Sciences, and the Rangely Advisory Committee of the U.S. Geological Survey.

FACULTY PUBLICATIONS

Recent publications and conference papers by faculty members and graduate students of the Cornell College of Engineering are listed. The names of Cornell personnel are in italics. The section immediately following is a supplement to the Winter 1974 listing and comprises papers published or presented during the period May through July 1973. A few earlier publications are also included, with the date shown in parentheses.

■ APPLIED AND ENGINEERING PHYSICS

Ahl, J. L., and *Cool, T. A.* 1973. Vibrational relaxation in the HF-HCl, HF-HBr, HF-HI, and and HF-DF systems. *Journal of Chemical Physics* 58:5540–5548.

Batterman, B. W., Maracci, G.; Merlini, A.; and Pace, S. 1973. Diffuse Mössbauer scattering applied to dynamics of phase transformations. *Physical Review Letters* 31:227–230.

Ignatiev, A., and *Rhodin, T. N.* 1973. Energy and temperature dependence of low-energy-electron diffraction from xenon single crystals. *Physical Review B* 8(2):893–906.

Lewis, A. 1973. Molecular Description of Photobiological Chromophores. Paper read at Meeting of the American Society for Photobiology, 10–14 June 1973, in Sarasota, Florida.

———. 1973. Laser Raman spectroscopy—a selective probe. *Biophysical Society Abstracts* 13:121a.

Lewis, A., and Pace, E. L. 1973. Vibrational spectra of molecular crystals. *Journal of Chemical Physics* 58:3661–3668.

Nelkin, M. 1973. Intermittency in fully developed turbulence as a consequence of the Navier-Stokes equations. *Physical Review Letters* 30:1029–1031.

Tong, S. Y.; Rhodin, T. N.; and *Ignatiev, A.* 1973. Layer dependent surface mean-square vibration amplitudes by low-energy-electron diffraction. *Physical Review B* 8(2):906–913.

Tong, S. Y.; Rhodin, T. N.; and *Tait, R. H.* 1973. t-matrix approach in low-energy-electron diffraction. Application of the t-matrix-perturbation method to the analysis of low-energy-electron-diffraction spectra for aluminum. *Physical Review B* 8(2):421–430; 430–440.

■ CHEMICAL ENGINEERING

Anderson, J. L., and Quinn, J. A. 1973. Charge Transport in Microcapillaries: Studies with Track-Etched Membranes. Paper read at 143rd Meeting of the Electrochemical Society, 13–18 May 1973, in Chicago, Illinois.

Manning, A. J., and *Rodriguez, F.* 1973. Predicting solubilities of vinyl polymers. *Journal of Applied Polymer Science* 17:1651–1662.

Rodriguez, F. 1973. Graphical solution of the Martin equation. *Journal of Polymer Science*, Part B, 11:485–486.

Stevenson, J. 1973. Flow in a tube with a circumferential wall cavity. *Journal of Applied Mechanics* (ASME) 40:355–361.

■ CIVIL AND ENVIRONMENTAL ENGINEERING

Bereano, P. L. 1973. A Matrix-Based Decision-Making Methodology. Paper read at 1st International Conference on Technology Assessment, 27 May–6 June 1973, at The Hague, The Netherlands.

———. 1973. Review of *Electricity and the environment: the reform of legal institutions* (N.Y.C. Bar Association). *Cornell Law Review* 58:1068–1075.

Bereano, P. L., et al. 1973. A proposed methodology for assessing alternative technologies. *Technology Assessment* 1:179–190.

Gallagher, R. H.; Liggett, J. A.; and *Chan, S. T. K.* 1973. Finite element shallow lake circulation analysis. *Proceedings of the ASCE, Journal of the Hydraulics Division* HY7:1083–1096.

Kato, B., and *McGuire, W.* 1973. Analysis of T-stub flange-to-column connections. *Proceedings of the ASCE, Journal of the Structural Division* 99(ST5):865–888.

Loh, G., and *White, R. N.* 1973. Factors influencing size effects in gypsum mortars. In *Proceedings of 4th Canadian Congress of Applied Mechanics*, ed. A. Bazergui; pp. 327–328. Montreal: CANCAM.

McGuire, W. 1973. Remodeling the Arecibo Radio Telescope. Paper read at Conference on Steel Developments, 21–25 May 1973, at the University of Newcastle, Newcastle, NSW, Australia.

Sangrey, D. A. 1973. Master of Civil Engineering at Cornell. Paper read at Annual Conference, Chairmen of Departments of Civil Engineering, 4 May 1973, at Lehigh University, in Bethlehem, Pennsylvania.

Shoemaker, C. 1973. Optimization of agricultural pest management II: Formulation of a control model. *Mathematical Biosciences* 17:357–365.

Singh, H.; Henkel, D. J.; and *Sangrey, D. A.* 1973. Shear and K_o swelling of overconsolidated clay. In *Proceedings of 8th international conference on soil mechanics and foundation engineering,* vol. 1, pp. 367–376. Moscow: International Society for Soil Mechanics and Foundation Engineering.

Slate, F. O. 1973. Low-Cost Housing, Primarily for Developing Nations—A New Course at Cornell University. Paper read at Workshop on Low-Cost Housing, 9–20 July 1973, at East-West Center, Honolulu, Hawaii.

White, R. N.; Gergely, P.; Laible, J. P.; and *Fajardo, O. A.* 1973. Seismic shear transfer across cracks in concrete nuclear reactor containment vessels. In *Proceedings of 5th world conference on earthquake engineering,* pp. 315–319. Rome, Italy: WCEE.

The following papers were published or presented during the period August through October 1973. A few earlier publications are also included, with the date shown in parentheses.

■ AGRICULTURAL ENGINEERING

Irwin, L. H. 1973. Design of High and Low-Volume Roads. Paper read at 44th Annual Conference of New York State Town Highway Superintendents, 17–19 September 1973, at Lake Placid, New York.

Levine, G.; Capener, H.; and *Gore, P.* 1973. *The management of irrigation systems for the farm.* Seminar report no. 2, Research and Training Network of the Agricultural Development Council.

Riley, J. G., and *Furry, R. B.* 1973. Simulation of the road-corrugation phenomenon. In *Soil compaction and corrugations,* Highway Research Record report no. 438, pp. 54–62. Washington, D.C.: Highway Research Board, National Research Council.

■ APPLIED AND ENGINEERING PHYSICS

Bachman, L., and *Salpeter, M.* 1973. Electron microscope autoradiography. Section in *Methods in electron microscopy (Meth. Elmi. 5 Lieferung.)* Berlin and Heidelberg: Springer-Verlag.

Elson, E. L., and *Webb, W. W.* 1973. Thermodynamic Fluctuations in Chemically Reacting Liquids. Paper read at Gordon Conference on Chemistry and Physics of Liquids, 13–17 August 1973, in Plymouth, New Hampshire.

Lewis, A. 1973. Tunable Laser Raman Spectroscopy in Biology. Paper read at Neutron Inelastic Scattering Conference, sponsored by the Atomic Energy Commission, 6–11 August 1973, at the Massachusetts Institute of Technology, Boston.

———. 1973. Tunable Laser Resonance Raman Spectroscopy of the Visual Process. Paper read at American Chemical Society Meeting Symposium on Lasers in Chemistry, 14–20 October 1973, in New York.

Liboff, R. L., and *Heitowit, E.* 1973. Application of a consistent kinetic equation to an inhomogeneous plasma. *Physics of Fluids* 16:1446–1455.

Liboff, R. L.; Nebenzahl, I.; and *Fleischmann, H. H.* 1973. On the radial momentum operator. *American Journal of Physics* 41:976–980.

Maresca, N. (student of *R. L. Liboff*). 1973. *Surface current construction of radiation spectra.* Report no. R1–74, Physics Branch, Office of Naval Research.

Salpeter, M. M. (1973). Sensitivity in electron microscope autoradiography. *Journal of Histochemistry and Cytochemistry* 21(7): 623–627.

Salpeter, M. M., and *Eldefrawi, M. E.* 1973. Sizes of end plate compartments, densities of acetylcholine receptor and other quantitative aspects of neuromuscular transmission. *Journal of Histochemistry and Cytochemistry* 21(9):769–778.

Salpeter, M. M., and McHenry, F. A. 1973. Electron microscope autoradiography, analysis of autoradiograms. Chapter in *Advanced techniques in biological electron microscopy,* ed. J. K. Koehler, pp. 113–151. New York: Springer-Verlag.

Van Wart, H. E.; Lewis, A.; Scheraga, H. A.; and Saeva, F. D. 1973. Disulfide bond dihedral angles from Raman spectroscopy. *Proceedings of the National Academy of Sciences (U.S.A.)* 70:2619–2623.

Webb, W. W. 1973. Fluorescence Correlation Spectroscopy. Informal presentation at Gordon Conference on Transport in Membranes, 27–31 August 1973, in Tilton, New Hampshire.

Wu, E. S., and *Webb, W. W.* 1973. The critical-vapor interface in SF_6. I. Thickness of the diffuse transition layer. II. Thermal excitations, surface tension, and viscosity. *Physical Review A* 8(4):2065–2076; 2077–2084.

■ CHEMICAL ENGINEERING

Ambler, C. M., and *Smith, J. C.* 1973. Centrifuges. In *Chemical engineers' handbook,* ed. R. H. Perry and C. H. Chilton, pp. 19.87–19.100. New York: McGraw-Hill.

Fields, R. D.; Rodriguez, F.; and *Finn, R. K.* 1973. Microbial degradation of polyesters: poly(caprolactone). In *Polymer preprints,* vol. 14, ed. J. E. McGrath, pp. 1244–1248. Washington: American Chemical Society, Division of Polymer Chemistry.

Fields, R. D., and *Rodriguez, F.* 1973. Microbial Degradation of Polyesters: Aliphatic Polyesters. Paper read at 5th Northeast Regional Meeting of the American Chemical Society, 14–17 October 1973, in Rochester, New York.

Finn, R. K. (1973). Methanol as a Fermentation Substrate. Paper read at 73rd Annual Meeting of the American Society for Microbiology, 6–11 May 1973, at Miami Beach, Florida.

Harriott, P.; Von Berg, R. L.; Wiegandt, H. F.; and *Dabby, S. S.* 1973. *Ice-brine separation in a bed of aggregates of fine ice crystals.* Report of Office of Saline Water, U.S. Department of the Interior.

Smith, J. C. 1973. Selection of a solids-liquid separator. In *Chemical engineers' handbook,* ed. R. H. Perry and C. H. Chilton, pp. 19.104–19.106. New York: McGraw-Hill.

■ CIVIL AND ENVIRONMENTAL ENGINEERING

Bisogni, J. J., and *Lawrence, A. W.* 1973. Kinetics of Microbially Mediated Methylation of Mercury in Aerobic and Anaerobic Aquatic Environments. Paper read at 46th Annual Conference of the Water Pollution Control Federation, 3 October 1973, in Cleveland, Ohio.

Brutsaert, W. 1973. Similarity functions for turbulence in neutral air above swell. *Journal of Physical Oceanography* 3:479–482.

DiPasquale, R. A. 1973. Cold-Formed Steel Framing System for Low Cost Modular Housing. Paper read at 2nd Specialty Conference on Cold-Formed Steel Structures, 22–24 October 1973, in St. Louis, Missouri.

Gallagher, R. H., and *Thomas, G. R.* 1973. The finite element method in plate and shell instability analysis. In *Proceedings of the 4th Australasian conference on structures and materials*, ed. P. Swannell, pp. 77–86. Brisbane, Australia: University of Queensland.

Meyburg, A. H., and Stopher, P. R. 1973. Towards trip attraction models for freight vehicle trips to shopping plazas. *Transportation Research Forum—Proceedings* XIV(1): 233–242.

Middleton, A. C., and *Lawrence, A. W.* 1973. Cost Optimization of Activated Sludge Wastewater Treatment Systems. Paper read at 166th National Meeting of the American Chemical Society, 30 August 1973, in Chicago, Illinois.

———. 1973. Least Cost Design of Activated Sludge Systems. Paper read at 46th Annual Conference of the Water Pollution Control Federation, 2 October 1973, in Cleveland, Ohio.

Sangrey, D. A.; Pollard, W. S.; and Cushing, J. P. 1973. Engineering landfill for reuse of the site. In *Proceedings of the international conference on land for waste management* (Ottawa, Canada), pp. 119–127.

Sangrey, D. A., and *White, R. N.* 1973. The Professional Program in Civil Engineering at Cornell University. Paper read at Annual Meeting of the American Society of Civil Engineers, 30 October 1973, in New York.

Stopher, P. R., and *Meyburg, A. H.* 1973. User and non-user perceptions of a small urban area bus system: an exploratory investigation. *Transportation Research Forum —Proceedings* XIV(1):539–552.

Weisman, R. N., and *Brutsaert, W.* 1973. Evaporation and cooling of a lake under unstable atmospheric conditions. *Water Resources Journal* 9:1242–1257.

White, R. N. 1973. Model Tests on Complete Structures. Paper read at Fall Convention of the American Concrete Institute, 7–12 October 1973, in Ottawa, Canada.

———. 1973. Structural joints—an overview. In *Proceedings of the 87th annual congress of the Engineering Institute of Canada*, ed. P. J. Harris, pp. 163–164 (abstract). Montreal: EIC.

White, R. N., and Chowdhury, A. H. 1973. Behavior of multi-story reinforced concrete frames subjected to severe reversing loads. In *Proceedings of the IABSE symposium on resistance and ultimate deformability of structures acted on by well defined repeated loads.* Zurich: International Association for Bridge and Structural Engineering.

■ COMPUTER SCIENCE

Bunch, J. R. 1973. Complexity of sparse elimination. In *Complexity of sequential and parallel numerical algorithms*, ed. J. F. Traub, pp. 197–220. New York and London: Academic Press.

Gries, D. 1973. Describing an algorithm by Hopcroft. *Acta Informatica* 2:97–109.

Hartmanis, J. 1973. On the problem of finding natural computational complexity measures. In *Mathematical foundations of computer science*, pp. 95–103. Mathematical Institute of the Slovak Academy of Sciences.

Hopcroft, J., and *Musinski, J.* 1973. Duality applied to the complexity of matrix multiplication and other bilinear forms. *SIAM Journal on Computing* 2:159–173.

Hopcroft, J. E., and *Tarjan, R. E.* 1973. Dividing a graph into triconnected components. *SIAM Journal on Computing* 2:135–158.

Salton, G. 1973. Proposals for a dynamic library. *Information* (Part 2) 2(3):5–27.

■ ELECTRICAL ENGINEERING

Antonsen, T., and *Ott, E.* 1973. Shear Driven Instabilities of an Unneutralized Electron Beam. Paper read at Annual Meeting of the Plasma Physics Division, American Physical Society, 31 October–3 November 1973, in Philadelphia, Pennsylvania.

Ballantyne, J. M.; Baukus, J. P.; and Lavin, J. M. 1973. Properties of light-modified-breakdown detector in GaAs. *Applied Optics* 12:2486–2493.

Ballantyne, J. M., and *Tang, C. L.* (1973). Nonlinear and Active Optical Devices. Paper read at NSF 2nd Grantee-User Conference on Optical Communications, 15 May 1973, at Berkeley, California.

Brice, N. M. 1973. Radiophysics of Jupiter. Paper read at NATO Advanced Study Institute, 14–24 August 1973, in Sheffield, England.

Brice, N., and *Lucas, C.* 1973. Cold Plasma Injection in the Magnetosphere. Paper read at Workshop on Controlled Magnetosphere Experiments, Second General Scientific Assembly, IAGA, 9–21 September 1973, in Kyoto, Japan.

Brice, N. M.; McDonough, T. R.; and *Williams, G. J.* 1973. The Radiation Belt and Magnetosphere of Jupiter. Paper read at Symposium on Planetary Atmosphere and Exosphere, Second General Scientific Assembly, IAGA, 9–21 September 1973, in Kyoto, Japan.

Camp, W. O.; Woodard, D. W.; and *Eastman, L. F.* 1973. Bias tuneable C. W. transferred electron devices. In *Proceedings of the 4th biennial Cornell electrical engineering conference*, pp. 177–183. Ithaca, New York: Cornell University.

Capranica, R. R. 1973. Detection of Species-Specific Signals in the Auditory System of Anurans. Invited address at the XIII International Ethological Congress, 14–24 August 1973, in Washington, D. C.

Capranica, R. R., and *Moffat, A. J. M.* 1973. Excitation, Inhibition, and "Disinhibition" in the Inner Ear of the Toad (*Bufo*). Paper read at 86th Meeting of the Acoustical Society of America, 30 October–2 November 1973, in Los Angeles, California.

Carlin, H. J. 1973. A simplified circuit model for microstrip. *IEEE Transactions on Microwave Theory and Techniques* MTT 21 (9):589–591.

Dalman, G. C., and *Lee, C. A.* 1973. High power silicon IMPATT amplifiers with low phase distortion. In *Proceedings of the 4th biennial Cornell electrical engineering conference*, pp. 339–348. Ithaca, New York: Cornell University.

Dragsten, P. D.; Webb, W. W.; Paton, J. A.; and *Capranica, R. R.* 1973. Sensitive Acoustic Vibration Measurements by Optical Heterodyne Detection of Scattered Laser Light. Paper read at 86th Meeting of the Acoustical Society of America, 30 October–2 November 1973, in Los Angeles, California.

Frey, J., and *Lee, C. A.* 1973. Plasma injection and efficiency in N and P type TRAPATT diodes. In *Proceedings of the 4th biennial Cornell electrical engineering conference*, pp. 401–408. Ithaca, New York: Cornell University.

Hagen, J. B., and *Farley, D. T.* 1973. Digital-correlation techniques in radio science. *Radio Science* 8(8,9):775–784.

Johnson, M.; Kribel, R.; Sudan, R.; and *Wharton, C.* 1973. Whistler Wave Studies. Paper read at Annual Meeting of the American Physical Society, Division of Plasma Physics, 31 October–3 November 1973, in Philadelphia, Pennsylvania.

Kim, M. 1973. The effects of metabolic inhibitors on and a nonlinear oscillator model of pacemaker neurons. In *Regulation and control in physiological systems*, ed. A. S. Iberal and A. C. Guyton, pp. 553–556. Pittsburgh: Instrument Society of America Press.

Klein, H. H.; *Ott, E.;* and Manheimer, W. 1973. Parametric Sidescatter of a Laser Beam in an Inhomogeneous Plasma. Paper read at Annual Meeting of the Plasma Physics Division, American Physical Society, 31 October–3 November 1973, in Philadelphia, Pennsylvania.

Korn, P.; Sandel, F.; and *Wharton, C.* 1973. Plasma heating with a relativistic electron beam. In *Proceedings of the 6th European conference on controlled fusion,* B. B. Kadomtsey, ed.; pp. 503–506. Moscow: USSR Academic of Sciences.

———. 1973. Relativistic electron beam heating of fully ionized plasma. *Physical Review Letters* 31:579–581.

Lee, C. A., and *Frey, J.* (1973). Comparison of plasma formation in n+p and p+n TRAPATT diodes. *Electronics Letters* 9(14): 318–320.

McDonough, T. R., and *Brice, N. M.* 1973. A Saturnian gas ring and recycling of Titan's atmosphere. *Icarus* 20:136–145.

———. 1973. The Saturnian "Hydrogen Doughnut" Hypothesis. Paper IAU no. 65 read at International Astronomical Union/COSPAR Symposium on Exploration of the Planetary System, September 1973, in Torun, Poland.

———. 1973. The Titanian Gas Ring of Saturn. Paper read at Symposium on Planetary Atmosphere and Exosphere, Second General Scientific Assembly, IAGA, 9–21 September 1973, in Kyoto, Japan.

McIsaac, P. R. 1973. Vacuum electronic devices. Chapter 4 in *Problems in physical electronics,* ed. R. L. Ferrari and A. K. Jonscher. London: Pion Limited.

Moffat, A. J. M., and *Capranica, R. R.* 1973. Sensory Processing in the Peripheral Auditory System of Treefrogs (*Hyla*). Paper read at 86th Meeting of the Acoustical Society of America, 30 October–2 November 1973, in Los Angeles, California.

Mondelli, A., and *Ott, E.* 1973. Straight Toroidal Plasma Equilibria with an Intense Relativistic Current Component. Paper read at Annual Meeting of the Plasma Physics Division, American Physical Society, 31 October–3 November 1973, in Philadelphia, Pennsylvania.

Murray, M. K., and *Capranica, R. R.* 1973. Spike generation in the lateral-line afferents of *Xenopus laevis:* evidence favoring multiple sites of initiation. *Journal of Comparative Physiology* 87:1–20 .

Ott, E.; Manheimer, W. M.; and Klein, H. H. 1973. Laser Scatter and Self-focusing in a Hot Low Density Plasma. Paper read at Annual Meeting of the Plasma Physics Division, American Physical Society, 31 October–3 November 1973, in Philadelphia, Pennsylvania.

Paton, J. A.; Capranica, R. R.; Loftus-Hills, J. J.; Dragsten, P. R.; and *Webb, W. W.* 1973. Mechanical Sensitivity of Acoustic Receptor Organs in Crickets. Paper read at 86th Meeting of the Acoustical Society of America, 30 October–2 November 1973, in Los Angeles, California.

Roome, W. D., and *Torng, H. C.* 1973. Algorithms for multiple shift register realizations of sequential machines. *IEEE Transactions on Computers* C–22:933–943.

Sprangle, P.; Manheimer, W.; *Ott, E.;* and Haber, I. 1973. Linear and Nonlinear Theory of Microwave Emission by Velocity-Space Instabilities of Relativistic Electron Beams. Paper read at Annual Meeting of the Plasma Physics Division, American Physical Society, 31 October–3 November 1973, in Philadelphia, Pennsylvania.

Swartz, W. E.; Brice, N.; and *Rowe, J.* 1973. A Visual Examination of Ionosphere Dynamics over Arecibo. Paper read at Symposium on Dynamics, Chemistry, and Thermal Processes in the Ionosphere and Thermosphere, Second General Scientific Assembly, IAGA, 9–21 September 1973, in Kyoto, Japan.

Turner, J. J.; Chen, B.; Yang, L.; Ballantyne, J. M.; and *Tang, C. L.* 1973. Gratings for integrated optics fabricated by electron microscope. *Applied Physics Letters* 23:333–334.

Wharton, C. 1973. *Studies of turbulent heating of a fusion plasma.* Report no. 0022 of the Office of Naval Research.

Williams, J. H., and Szymanski, T. G. 1973. Non-canonical parsing. In *Proceedings of the 14th annual symposium on switching and automata theory,* pp. 122–129. New York: IEEE.

Wood, C. E. C.; Wrick, V., III; and *Eastman, L. F.* 1973. Pulsed InP LSA devices grown by solution epitaxy. In *Proceedings of the 4th biennial Cornell electrical engineering conference,* pp. 147–154. Ithaca, New York: Cornell University.

■ GEOLOGICAL SCIENCES

Ingle, J. C.; *Karig, D. E.;* et al. 1973. Western Pacific-DSPD Leg 31. *Geotimes* 18:22–25.

Karig, D. E. 1973. Comparison of island arc-marginal basin complexes in the Northeast and Southwest Pacific. In *The western Pacific: island arcs, marginal seas, geochemistry,* ed. P. J. Coleman, pp. 355–364. New York: Crane, Russak.

Oliver, J. 1973. Island arcs. *Encyclopedia Britannica,* pp. 1026–1030.

Oliver, J.; Kelleher, J.; and Sykes, L. 1973. Possible criteria for predicting earthquake locations and their application to major plate boundaries of the Pacific and the Caribbean. *Journal of Geophysical Research* 78:2547–2585.

Oliver, J.; Pascal, G.; Dubois, J.; *Barazangi, M.;* and *Isacks, B.* 1973. Seismic velocity anomalies beneath the New Hebrides island arc: evidence for a detached slab in the upper mantle. *Journal of Geophysical Research* 78:6998–7004.

Schubert, G., and *Turcotte, D. L.* 1973. Waves on a phase change boundary. *Geophysical Fluid Dynamics* 5:191–199.

Turcotte, D. L., and Oxburgh, E. R. 1973. Mid-plate tectonics. *Nature* 244:337–339.

■ INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH

Billera, L. J., and Bixby, R. E. 1973. Characterizing Market Games Without Side Payments. Paper read at 8th International Symposium on Mathematical Programming, 27–31 August 1973, at Stanford University, Stanford, California.

Fulkerson, D. R. 1973. Results on Blocking Pairs of Matrices. Paper read at 8th International Symposium on Mathematical Programming, 27–31 August 1973, at Stanford University, Stanford, California.

Garfinkel, R. S., and *Nemhauser, G. L.* 1973. An introduction to integer programming and its applications. In *Optimization and design,* ed. M. Avriel, M. J. Rijckaert, and D. J. Wilde, pp. 443–472. New York: Prentice-Hall.

Gupta, S. S., and *Santner, T. J.* 1973. On selection and ranking procedures—a restricted subset selection rule. In *Contributed papers of the 39th session of the International Statistical Institute* (held 20–30 August 1973, in Vienna, Austria), vol. 1, pp. 409–417.

■ MATERIALS SCIENCE AND ENGINEERING

Blakely, J. M. 1973. *Introduction to the properties of crystal surfaces.* Oxford, England: Pergamon Press.

Blakely, J. M., and *Danyluk, S.* 1973. Space charge regions at silver halide surfaces:

effects of divalent impurities and halogen pressure. *Surface Science* 40:37–60.

———. 1973. *Variation of surface potential with temperature and orientation for silver halide crystals.* Report no. 2075, Materials Science Center, Cornell University.

Lincoln, R. C., and *Ruoff, A. L.* 1973. Absolute length measurement at high pressure. *Review of Scientific Instruments* 44(9):1239–1246.

Patil, H. R. 1973. *On the structure in the true secondary electron peak from clean and graphite covered Ni(111) surface.* Report no. 2108, Materials Science Center, Cornell University.

Roberto, J.; Batterman, B. W.; and *Keating, D. T.* 1973. Forbidden (222) neutron reflection in germanium, anharmonicity in the nuclear motion. *Physica Status Solidi (b)* 59:K59–K61.

Ruoff, A. L.; Lincoln, R. C.; and Chen, Y. C. 1973. A new method of absolute high pressure determination. *Journal of Physics D: Applied Physics* 6:1295–1306.

Thomas, E. L., and *Sass, S. L.* 1973. A new defect in polyethylene single crystals. In *Proceedings of the 31st annual meeting of the Electron Microscopy Society of America,* ed. C. J. Arceneaux. New Orleans: Electron Microscopy Society of America.

Wilson, K. L., and *Seidman, D. N.* 1973. A field ion microscope study of the point defect structure of a depleted zone in ion (W+) irradiated tungsten. In *Defects and defect clusters in B.C.C. metals and their alloys.* Nuclear Metallurgy Series, vol. 18, ed. R. J. Arsenault, pp. 216–239. Gaithersburg, Maryland: National Bureau of Standards.

■ MECHANICAL AND AEROSPACE ENGINEERING

de Boer, P. C. T., and Fozo, S. R. 1973. *Precision and atomization in fuel metering.* Engineering report no. 1008, Engine Division, Ford Motor Company.

Gill, P. M., and *Seebass, A. R.* 1973. Nonlinear Acoustic Behavior at a Caustic: An Approximate Analytical Solution. Paper read at AIAA Aero-Acoustics Specialists' Conference, 15–17 October 1973, in Seattle, Washington.

Gouldin, F. C., and Yue, B. 1973. Kinetic Study of Two-Stage Combustion in MHD Topping Cycles. Paper read at Fall Meeting of the Eastern States Section of the Combustion Institute, 11–12 October 1973, in Montreal, Canada.

Kopecky, R. M., and *Torrance, K. E.* 1973. Initiation and structure of axisymmetric eddies in a rotating stream. *Computers and Fluids* 1:289–300.

Krauter, A. 1973. Steady state cornering of two-wheeled vehicles. *Journal of Applied Mechanics* 40:119–121.

McLean, W. J.; Miller, J. A.; *Resler, E. L., Jr.;* and *Bauer, S. H.* 1973. Early Stages in the Mechanism of Methane Pyrolysis and Oxidation. Paper on Chemical and Physical Processes in Combustion, read at 1973 Technical Meeting of the Eastern Section of the Combustion Institute, 11–12 October 1973, in Montreal, Canada.

McManus, H. N., Jr., ed. 1973. *A reusable lunar shuttlecraft (RLS): a systems study.* Report prepared under NASA contract no. NGR 33-010-071.

Moore, F. K. 1973. On the minimum size of large dry cooling towers with combined mechanical and natural draft. *Journal of Heat Transfer* 95:383–389.

Robb, B. S., and *Turcotte, D. L.* 1973. Laser produced hemispherical shock waves. *AIAA Journal* 11(6):836–840.

Seebass, A. R. 1973. The Design or Operation of Aircraft to Minimize their Sonic Boom. Paper no. 73-817, read at AIAA 5th Aircraft Design, Flight Test and Operations Meeting, 6–8 August 1973, in St. Louis, Missouri.

Turcotte, D. L.; Torrance, K. E.; and Hsui, A. T. 1973. Convection in the Earth's mantle. In *Methods in computational physics,* vol. 13, pp. 431–454. New York: Academic Press.

Wang, K. K. 1973. *Friction welding research.* Final report to the Welding Research Council.

■ THEORETICAL AND APPLIED MECHANICS

Burns, J. A. 1973. Asteroid Rotation. Paper read at Planetary Dynamics Conference, 8–9 October 1973, at Ohio State University in Columbus.

Burns, J. A., and *Burns, J. K.* 1973. Kinetic art: a mural of variably stressed photoelastic material with light polarizers. *Leonardo* 6:325–328.

Dunn, J. C. 1973. Inversion of normal operators by polynomial interpolation. *Proceedings of the American Mathematical Society* 40(1):225–228.

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