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The Center for Energy Studies is a multidisciplinary research center, the central liaison for energy research, education, and public service at The University of Texas at Austin. Dr. Herbert H. Woodson is director.

Editor: Jennifer Evans

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SRP Researchers Study Polymer Membranes for Separating Gases

Plastic membranes almost as thin as the wall of a human cell are the basis for a new technology for separating gases. Researchers in the Separations Research Program (SRP) of the Center for Energy Studies are studying ways to understand and improve these new membranes.

The intangibility of gases has long frustrated scientists and engineers seeking an inexpensive, reliable way to unmix them. Gas separation by synthetic membranes holds promise as a less energy intensive competitor against existing techniques such as cryogenic distillation and solvent extraction and recovery.

Inexpensive gas separation could generate large quantities of oxygen, carbon dioxide, helium, hydrogen, and many other gases for which the market is now limited because the cost of producing them is high.

Since the 1830s, it has been known that thin membranes tend to block some gases and allow others to pass through freely. The earliest membranes tested with gases were of india rubber. But for all known materials, the membrane permeation rate (the rate that gas molecules pass through it) was very slow until a few years ago.

In recent years numerous breakthroughs have allowed very thin, very efficient membranes to be cast from polymers. The asymmetric membrane is the leading type. It is called asymmetric because it is formed of two layers: a

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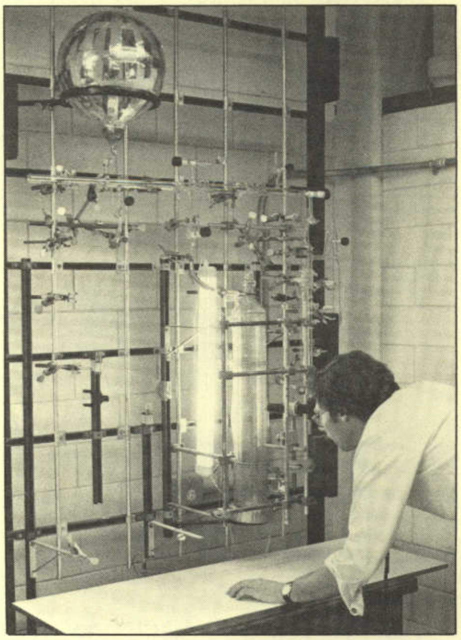
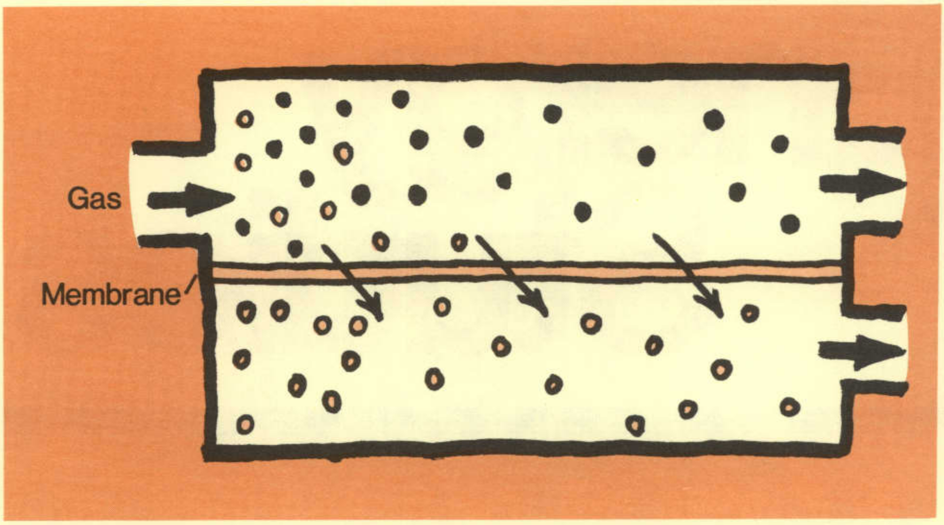


SRP researcher William Koros measures the weight gained by a tiny membrane sample as it sorbs, or takes in, gas. A weight gain of 500 millionths of a gram indicates a highly sorbent material.



With an efficient gas-separating membrane, molecules of one kind of gas travel across the membrane, but molecules of other gases do not.

thin, dense layer that performs the separation and a thick, foamlike layer that provides support and durability.

A membrane sheet placed in a frame is not an efficient separation device because its output is low. Membrane units such as bundles of hollow membrane fibers or spirally wound multiple sheets have much higher surface-to-volume ratios.

Such membranes are beginning to be used industrially in several ways:

- ☐ Separating hydrogen from methane in refineries, from carbon monoxide in syngas and oxy-alcohol plants, and from nitrogen in ammonia synthesis
- ☐ Enriching air with nitrogen to be used to blanket flammable petroleum products during transport to reduce the risk of fire
- ☐ Enriching air with oxygen for medical use and for enhancing combustion in furnaces
- ☐ Recovering and recycling carbon dioxide that has been injected below ground into oil reservoirs, an enhanced recovery technique

Gas membrane separations is an infant industry, barely five years old. Many in the field expect it to boom in the next decade, as further improvements are achieved.

"Head to head with traditional technologies." Gas membranes are one of the main research areas in the Separations Research Program. The effort is headed by Dr. Donald R. Paul, professor and chairman of the UT Department of Chemical Engineering, and Dr. William J. Koros, research engineer at the center. In addition to the SRP industrial support, funding for the research also comes from the National Science Foundation and the US Navy.

"We want to build up enough sound, reliable data so that membranes don't have to be created from scratch each time," Dr. Koros said. "A lot of processes are operating. Almost no fundamental data have been gathered on them. No one really knows exactly how to predict their behavior."

Donald Paul

Their goal is to build up comprehensive data about the properties of different membrane materials under different operating conditions. "Membranes are coming head to head with traditional technologies that have been highly optimized. . . . We want to get them quickly on a good foundation."

In his present research, Dr. Koros is studying a fundamental aspect of membrane science: how much of a gas will *sorb,* or go into, a certain membrane sample under varying conditions of temperature and pressure. The weight of the membrane changes infinitesimally when gas sorbs into it. The weight change is measured with a microbalance, essentially a delicate spring made of quartz.

In other sorption studies, a membrane is exposed to a pressurized chamber filled with a gas, then left to stabilize. The pressure changes are measured to derive the amount of gas sorbed.

To examine permeability, the researchers reinforce a membrane sample and place it between two chambers, one filled with gas under pressure and the other containing a vacuum. Pressure increases in the empty chamber indicate how much gas has permeated across the membrane.

The researchers will conduct hundreds, perhaps thousands, of trials on different combinations of membranes, gases, and operating conditions.

A superior gas membrane will possess high permeation and selectivity rates with adequate durability, especially at high temperatures, Dr. Paul said.

A basic question facing membrane researchers is how to go about searching for high-performance polymers. Extensive testing certainly must be part of the approach, but the SRP researchers hope to bypass a great deal of testing by creating good theoretical models.

The ideal gas membrane. Drs. Paul and Koros have a working hypothesis about what makes an ideal gas membrane.

First, *adequate rigidity,* of "a stiff molecular backbone," as Dr. Koros termed it. A polymer that is softened or rubbery makes a poor membrane because it is not selective enough. Molecules can easily push their way through a stretchy membrane, but a rigid structure is more selective—open to some gases but not others. Glassy polymers seem to be most promising.

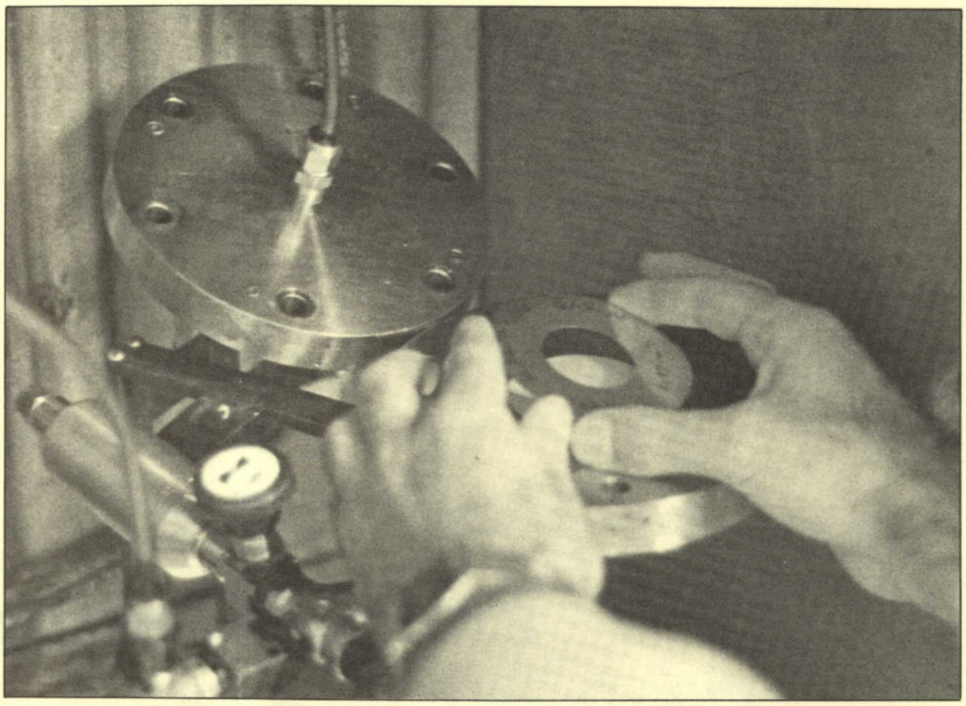
Second, *gaps in the molecular matrix.* A crystalline-type polymer has almost no gaps and thus almost no permeability. The molecular chains are too closely packed. In amorphous (i.e., noncrystalline) polymers of open structure, gaps do exist, allowing gas molecules to pass through. But gaps of too large a size again seem to diminish selectivity.

Third, *chemical affinity.* A membrane with a chemical affinity for a certain gas tends to cause more molecules of that gas to dissolve into it, thus improving its performance.

Recent studies by Drs. Paul and Koros have turned up some interesting discoveries about the properties of gas membranes.

One study dealt with the selectivity of a highly permeable membrane. The researchers sought to learn whether the selectivity could be improved by adding small molecules to the membrane's open chemical structure, thereby "tightening it up." This technique is called *antiplasticization,* because it also makes the polymer less plastic.

The researchers found that the small molecules could indeed make a membrane more selective (possibly by making the gaps smaller), but at the same time reduced the membrane's permeation rate substantially. Whether higher selectivity can be achieved without much sacrifice of permeability is an issue that future research may resolve.



Graduate student Jamal Elhibri unloads a polyvinyl chloride membrane sample after measuring its performance in a high-pressure gas permeation device.

Blends and fluorination. In studies of combinations of polymers, Dr. Paul found "in some cases two-polymer blends can be more selective together than either pure polymer alone." Interesting results were obtained with a blend of poly(phenylene oxide) and polystyrene.

Another characteristic of membranes is known as the permeability coefficient. It is a performance value that expresses the amount of gas going through the membrane per psi of pressure difference across the membrane. The researchers have studied the permeability coefficients of numerous membrane materials.

The permeability coefficient of nearly all membranes decreases as pressure increases, within the usual range of 20 to 25 atmospheres (300 to 500 psi). That is, higher pressure does cause more gas to pass through the membrane, but the increase gets smaller and smaller—a pattern of diminishing returns.

"For ten years, that is what we have seen. Now, in a very few cases, we are seeing the opposite," Dr. Paul said.

"Why does one polymer's permeability go up and another go down with increasing pressure? We have ideas, but they are still under test," Dr. Paul said. What such polymers will do under even higher pressures is not yet known and is a subject for future SRP research.

A third area of study has been the effect of fluorine on membranes. Dr. Paul and chemical engineering graduate student Carol Kiplinger have tested a partial fluorination technique created by Dr. Richard J. Lagow, UT professor of chemistry.

The surface of a polyethylene membrane was treated with fluorine and then exposed to gases. The fluorine made the membrane less permeable to methane and carbon dioxide but not to helium. Thus the technique may hold commercial promise as a way to recover helium from natural gas, Dr. Paul said.

These SRP projects and future ones emphasize the kind of research useful to companies yet unlikely to be carried out by them.

"We don't tend on our own to get very heavily involved in applications, and companies don't tend to get very heavily involved in fundamentals," Dr. Paul said. The interplay between the two is likely to contribute substantially to gas membrane technology in the next several years.

Want to receive CES Executive Summaries?

To be included on the mailing list to receive executive summaries of major Center for Energy Studies research reports, both technical and policy-related, please send your name, affiliation or organization, address, and area(s) of interest to: Jennifer Evans, Center for Energy Studies, ENS 143, The University of Texas at Austin, Austin, Texas 78712.

UT's Energy-Related Courses and Degree Plans

If you are a UT student interested in learning about energy or in pursuing an energy-related career, The University of Texas at Austin offers a variety of opportunities for you. More than 170 undergraduate and 200 graduate courses are offered on different aspects of energy, including energy technology, public policy, conventional production, alternative sources, energy-conscious design, economic issues, and many other topics.

Not every course is offered every semester; some are added as others are dropped. If a course listed here does not appear in a current course catalogue, you can inquire with the department office about when it will be offered again.

The university offers about 40 degrees with program concentrations related to energy. They also are listed below. To learn more about the specific requirements of an undergraduate degree, refer to the catalogue of that college or school; for all graduate degrees, refer to the graduate school catalogue. These publications can be purchased from the Registrar, MAI 1, UT-Austin, Austin, Texas 78712.

* Denotes graduate course.

ARCHITECTURE

ARC 340M	Environmental Controls
ARC 340N	Environmental Controls II
ARC 141L	Environmental Controls Lab
ARC 355	Alternate Energy Systems Seminar
ARC 355	Application of Energy Methods in Architecture
ARC 355	Energy Methodology
ARC 355	Manual Methods of Energy Analysis
ARC 380*	Alternate Energy Systems
ARC 380*	Application of Energy Methods in Architecture
ARC 380*	Computer Methods of Energy Analysis
ARC 380*	Daylighting
ARC 380*	DEROB Simulation
ARC 380*	Energy-Conserving Design with Mechanical Equipment
ARC 380*	Energy Simulation in Architecture
ARC 380*	Manual Methods of Energy Analysis
ARC 380*	Passive Solar Analysis
ARC 380*	Survey of Environmental Control Systems II
CRP 355	Environmental Policy
CRP 383*	Coastal Zone Planning
CRP 383*	Environmental Policy
CRP 384K*	Natural Resources and Environment Workshop

BUSINESS ADMINISTRATION

BA 279	Problems in Business Administration: Resources
BA 391*	Special Studies in Business Administration: Legal-Environmental-Business
BA 391*	Special Studies in Business Administration: Resources
BA 691*	Special Studies in Business Administration: Resources
BL 370	Government and Business Topics: Environmental Law
BL 372	Oil and Gas Law
IB 350	International Trade
IB 363	International Commercial Relations and Policies
IB 370/ RES 370	World Resources and International Trade
IB 395*	Seminar: International Trade
MAN 385*	Technology Manage-

	ment—Focus on Oil Field Services Industry
MAN 387*	Technology Forecasting and Assessment
RES 326	Texas' Resources and Industries
RES 361	Introduction to the Study of Resources
RES 363	Resources of Industry
RES 394*	Seminar: Resources
TR 350	Transportation Systems and Services
TR 361	Mass Transportation and Urban Problems
TR 362	Management of Transportation Enterprises
TR 370	Transportation and Logistics
TR 375	Transportation Regulation and Policy
TR 395*	Seminar: Logistics and Transportation

ENGINEERING

ARE 345	Water, Sanitary, and Electrical Systems in Buildings
ARE 345Q	Mechanical Equipment of Buildings
ARE 259	Environmental Problems for Architecture Majors
ARE 360	Principles of Comfort Control
ARE 361	Building Investment Analysis
ARE 363/ ME 364K	Air Conditioning and Refrigeration
ARE 385*	Project Management—Pipeline Projects
ARE 385N*	Construction Management—Offshore Construction
CE 341	Environmental Pollution Engineering
CE 342	Water Pollution Control
CE 345	Industrial Hygiene and Toxicology
CE 346	Solid Waste Engineering

(Refer to the College of Engineering Catalogue for a full descriptive list of more than 30 civil engineering courses on ***air and water pollution control, environmental health engineering, and atmospheric science***.)

CE 358	Introductory Ocean Engineering
CE 377K	Studies in Civil Engineering: Energy Policy and Ethical Conflict
CE 377K	Hazardous Waste Management
CE 377K	Technical Innovation—Bioethical Issues
CE 380P*	Ocean Engineering Principles: Theory and Applications
CE 388M*	Radiological Health
CE 388P*	Environmental Engineering of Energy Systems
CE 397*	Ocean Engineering
CHE 322	Thermodynamics
CHE 354	Unit Operations I: Fluid Flow, Heat, and Mass Transfer
CHE 357	Technology and Its Impact on the Environment
CHE 363	Unit Operations II: Separation Processes
CHE 372	Chemical Reactor Design
CHE 373K	Process and Plant Design
CHE 384*	Introduction to Research: Advanced Concepts of Energy Technology
CHE 384*	Introduction to Research: Advanced Concepts of Enhanced Oil and Mineral Recovery
CHE 384*	Introduction to Research: Advanced Concepts of Thermodynamics
CHE 384*	Membrane Science and Engineering
CHE 387K*	Advanced Thermodynamics
CHE 388K*	Separations Processes
EE 102	Introduction to Electrical Engineering
EE 368	Electric Power Transfer and Distribution
EE 369	Power Systems Engineering
EE 379K	Relay Protection of Power Systems
EE 379K	Topics in Electrical Engineering—Energy Policy and Ethical Conflict
EE 379K	Topics in Electrical Engineering—Technical Innovation and Bioethics
EE 394J*	Economic Analysis of Energy Systems
EE 394J*	Energy Conversion Engineering
EE 394J*	Environmental Engi-

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UNDERGRADUATE DEGREES AND MAJORS

(programs or options in parentheses)

Architectural Engineering (Environmental Systems)
Architectural Engineering and Architecture—a six-year dual program
Architectural Studies
Architecture
Business Administration (Engineering Route to Business, Petroleum Land Management, World Resources and Industries, International Business)
Chemical Engineering (Environmental Improvement, Energy Resources)
Chemistry
Civil Engineering (Environmental Pollution)
Economics
Electrical Engineering (General Electrical Engineering, Power Systems and Energy Conversion)
Engineering Science (Environmental Engineering, Geological Engineering, Nuclear Engineering, Ocean Engineering)
Geography
Geological Sciences
Government
Interdisciplinary Engineering Program: Environmental Quality
Latin American Studies
Mechanical Engineering (Energy and Fluids Systems Engineering, Nuclear Engineering, Petroleum Industry Applications)
Middle Eastern Studies
Petroleum Engineering (Oil and Natural Gas Reservoir Engineering, Oil and Natural Gas Production Engineering, Petroleum Finance and Management)
Physics

GRADUATE DEGREES

(selected programs in parentheses)

Architectural Engineering (Environmental Systems)
Architecture (Energy Studies in Architecture)
Business Administration (Management of Technology, Regional Resources Management, Resources)
Chemical Engineering (Energy Resources, Environmental)
Chemistry
Civil Engineering (Environmental Health Engineering, Geotechnical Engineering, Ocean Engineering)
Economics (Resource and Energy Economics [in formation])
Electrical Engineering (Energy Systems, Plasma and Quantum Electronics)
Energy and Mineral Resources—a multidisciplinary master of arts degree program
Geography
Geology (Economic Geology of Nonmetals and Fluids, Environmental Geology)
Government
Latin American Studies
Law
Mechanical Engineering (Energy and Fluid Systems, Nuclear Engineering)
Petroleum Engineering
Physics (Nuclear Physics, Plasma Physics)
Public Affairs (Energy, Natural Resources)
Public Affairs and Business Administration—a joint master's degree

neering and Energy Systems

EE 394J*	Power Systems Engineering I
EE/ME 394J*	Applied Solar Energy
EE/ME 394J*	Economic Analysis of Energy Systems
EE/ME 394J*	Power Systems Engineering

(Refer to College of Engineering Catalogue for a full descriptive list of more than 30 electrical engineering courses on ***power systems engineering, plasma dynamics, and electrical systems***.)

EMR 396*	Seminar—Energy and Mineral Resources
ME 320	Applied Thermodynamics
ME 326	Thermodynamics I
ME 328	Thermodynamics II
ME 335K	Principles of Comfort Control
ME 337	Nuclear Engineering: Introduction to Nuclear Power Systems

(Refer to the College of Engineering Catalogue for a full descriptive list of more than 15 mechanical engineering courses on ***nuclear engineering and fusion engineering***.)

ME 339	Heat Transfer and Rate Processes
ME 351K	Engineering Considerations in Fusion Reactor Design
ME 360N	Intermediate Heat Transfer
ME 361G	Nuclear Reactor Operations
ME 361M	Thermodynamics of Materials
ME 362K	Readings in Engineering (problems of society, technology, and energy)
ME 363L	Energy Systems Laboratory
ME 364K	Air Conditioning and Refrigeration
ME 374L	Design of Thermal Systems
ME 374S	Solar Thermal Applications
ME 379K	Combustion Engine Processes
ME 381R*	Convection Heat Transfer
ME 381R*	Radiation and Heat Transfer
ME 381Q*	Thermodynamics
ME 382Q*	Design of Thermal and Fluid Systems
ME 387Q*	Thermodynamics of Materials
ME 388R*	Nuclear Radiation Shielding
ME 394J*	Energy Conversion Engineering
ME 394J*	Economic Analysis of Energy Systems
ME 394J*	Power Systems Engineering II
ME 397K*	Energy and Fluid Systems
ME 697*	Current Studies in Engineering: Combustion Science
ME 697*	Current Studies in Engineering: Electric Power in the Environment
ME 697*	Current Studies in Engineering: Nuclear Health Physics
ME 697*	Current Studies in Engineering: Solar Power Conversion
PEN 102	Introduction to Petroleum Engineering
PEN 320	Petroleum Exploration and Production (for nonengineering students)

(Refer to the College of Engineering Catalogue for a full descriptive list of more than 60 courses on ***petroleum engineering***).

LAW

LAW 341L*	Environmental Law
LAW 360N*	Regulated Industries (primarily transportation)
LAW 263P*	Advanced Oil and Gas
LAW 374N*	Taxation of Natural Resources
LAW 383N*	Federal Taxation of Oil and Gas
LAW 390*	Oil and Gas

LIBERAL ARTS

AMS 315	Environmental History
AMS 321	Environmental History of the United States
ANT 391*	Topics in Anthropology: Energy, Power, and Social Progress
ECO 330K	Energy Economics
ECO 360	Government Regulation of Industry

ECO 360M	Economies of the Middle East and North Africa
ECO 378M	Studies in Mineral Resources and Environmental Economics
ECO 384N*	Resource Economics
ECO 385L*	Advanced Natural Resources and Environmental Economics
ECO 391*	Environmental Economics
ECO 392M*	Introduction to Resource Systems Modeling
GOV 337M	Government and Politics of Mexico
GOV 356L	Government and Politics of the Middle East and North Africa
GOV 360N/ IS 320	International Organizations
GOV 365P	Politics of Oil
GOV 381L*	Energy Policy
GOV 390L*	Political Systems of the Middle East
GRG 325	Geography of Texas
GRG 327	Geography of USSR and Its Borderlands
GRG 327K/ IS 320	Energy and Society
GRG 328	Geography of the Middle East
GRG 334	Conservation, Resources, and Technology
GRG 335/ IS 320	Economic Activity and Resource Distribution
GRG 343K	Coastal Zone Geography
GRG 346/ IS 320	Human Use of the Earth
GRG 351	Man and Nature
GRG 352	Topics in Economic Geography: Topic 1. Resources and the Environment
GRG 355	Problems of Urban Transportation and Travel Behavior
GRG 356	Topics in Environmental Geography
GRG 372	Topics in the Geography of Latin America: Topic 5. Impact of Mining
GRG 372K	Proseminar in Environmental Geography
GRG 388*	Seminar in Resources and Conservation
GRG 393K*	Research in Remote Sensing of the Environment
MES 301K	Introduction to the Middle East
MES 324K	Modern Iran
MES 329	People, Petroleum, and Politics
PHL 322	Science and the Modern World

* Denotes graduate course.

NATURAL SCIENCES

BOT 308	Plants, Environment, and Human Affairs
BOT 340	Plants, Environment, and Human Affairs
BOT 349	Environmental Pollution
CH 305M	Science and the Environment
CH 390L*	Advanced Analysis of Electrochemical Methods
CH 397S*	Advanced Analysis of Electrochemistry
GEO 401K	Energy and Geology: Earth Limitations
GEO 330K	Petroleum Geology—Basin/Trend Analysis
GEO 335	Geology and Resources of Texas
GEO 341	Mineral Resources
GEO 344K	Marine Mining and Minerals
GEO 348	Environmental Geology—The Paradox of Humans and Earth
GEO 353	Environmental Geology
GEO 362K	Geology of Metallic Mineral Deposits
GEO 362L	Economic Geology of Nonmetallic Mineral Deposits
GEO 365K	Introduction to Geophysical Exploration
GEO 365L	Geophysical Exploration
GEO 365N	Geophysical Data Processing
GEO 365N	Geophysical Interpretation
GEO 368	Geology of Energy Resources
GEO 368L	Petroleum Geology: Occurrence and Exploration Concepts
GEO 368N	Application of Geology to Energy Resources
GEO 386L*	Geology of Petroleum
GEO 386M*	Petroleum Exploration Methods
GEO 390M*	Thermodynamics of Geologic Processes
GEO 391*	Economic Geology
GEO 391*	Internship in Environmental Geology
GEO 391E*	Petrology of Shales
GEO 391M*	Environmental Geology
GEO 391J	Mineral and Energy Resources: Geology, Economics, and Policy
GEO 394*	Research in Energy Resources
PHY 302K	General Physics—Technical Course: Mechanics, Heat, and Sound
PHY 302L	General Physics—Technical Course: Electricity and Magnetism, Light, Atomic and Nuclear Physics
PHY 303K	Engineering Physics I
PHY 303L	Engineering Physics II
PHY 316	Electricity and Magnetism
PHY 326	Introduction to Nuclear Physics
PHY 341	Selected Topics in Physics: Energy Production
PHY 341	Selected Topics in Physics: Physics of Air Pollution
PHY 352K	Classical Electrodynamics
PHY 380M*	Plasma Physics—Stability Theory
PHY 391M*	Nonlinear Plasma Theory
PHY 391S*	Seminar in Plasma Physics
PHY 397K*	Nuclear Physics

(Refer to the College of Natural Sciences Catalogue for other courses on ***physics, plasma physics, and nuclear physics***.)

PS 304	Introductory Physical Science II: Substances, Heat, Electricity

PUBLIC AFFAIRS

PA 388K*	Seminar on Environmental Problems and Policies
PA 388K*	Seminar on Contemporary Policy Issues
PA 693A*	Political Economy

CENTER FOR ENERGY STUDIES
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Engineering Science Building 143
Austin, Texas 78712

ADDRESS CORRECTION REQUESTED

CES Update

Office of Director

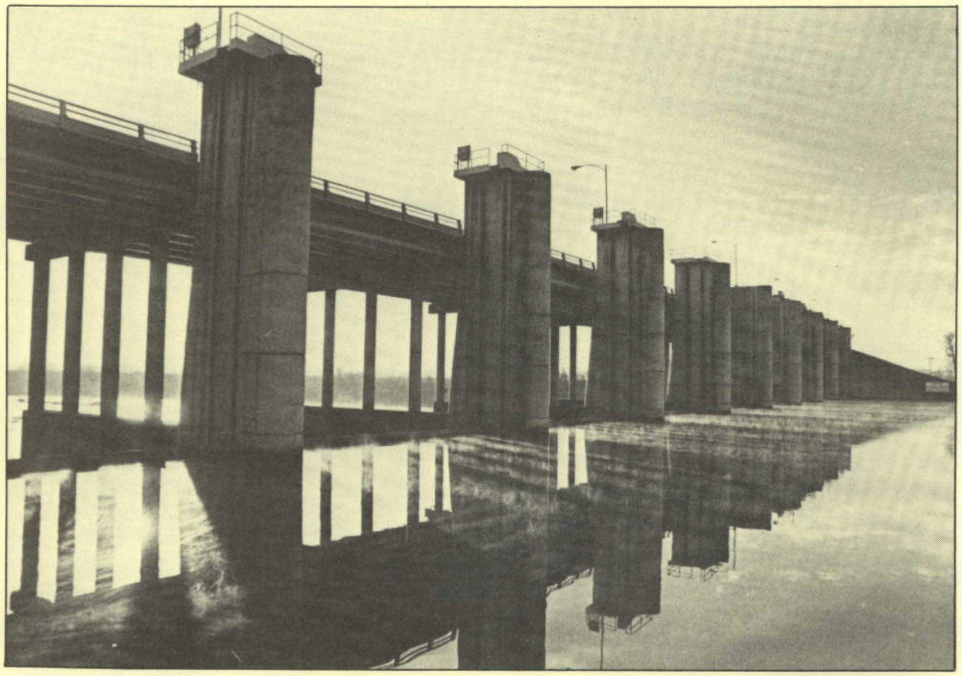
The City of Austin's **first hydroelectric plant,** a small one, has moved several steps closer to reality since CES researchers investigated its feasibility in 1981.

October 22 Austin voters approved $10 million in bonds to finance the hydro plant. The next steps, according to Chris E. Ioannou of the city's Power Production Department, are preliminary design, obtaining a federal permit (easily a six-month process), final design, and construction.

The low-head hydro unit will be designed to generate electricity from water falling over a 14-foot drop at the Austin Longhorn Dam on the Colorado River. Dr. Walter Moore, the UT professor of civil engineering who directed the feasibility study, said that the unit probably will not be constructed on the dam itself, but will be cut into the bank beside it. Some water flow will be diverted around the dam, through a turbine, and released downstream. A horizontal-type turbine looks most promising, he said.

One of the chief advantages of the unit is that it will use a source of energy that is essentially free, "water that has to be released anyway," said Dr. Moore. Another advantage is its minimal environmental impact. The structure that will house the turbine will be low and unobtrusive, he said.

Its chief disadvantage, aside from a cost of up to $10 million, is that the capacity will be small—3 megawatts—in a city where the past summer's peak demand for electricity was 1,101 megawatts, Mr. Ioannou said.



Longhorn Dam on the Colorado River is to become the first hydroelectric site in Austin, Texas (Photo courtesy of Austin History Center, PICA12575)