THE CENTER FOR ENERGY RESEARCH
PROPOSAL FOR CONTINUATION, 2004

Sunset Review of the Organized Research Unit
University of California, San Diego
Academic Year 2003-2004

University of California, San Diego
Center for Energy Research

THE UNIVERSITY OF CALIFORNIA, SAN DIEGO
CENTER FOR ENERGY RESEARCH
ENGINEERING BUILDING UNIT II
LA JOLLA, CALIFORNIA, 93093-0417

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1. GOALS AND OBJECTIVES OF CER

The goals and objectives of the Center for Energy Research can be summarized by the following mission statement:

> The purpose of the UCSD Center for Energy Research (CER) is to advance interdisciplinary programs of research and teaching broadly related to energy, providing graduate students, post-doctoral researchers, professional research staff and faculty with added research opportunities, facilities and assistance that would be unavailable to them without CER. CER serves important research, educational and public service functions that are not adequately met by the existing departments and other organized research units at UCSD, none of which focus specifically on energy. The need to address energy problems arises from factors which include: (i) the key role of energy usage in the functioning and growth of industrial society and developing nations, (ii) the finite supply of fossil-fuel resources and related issues of national security, (iii) the environmental side effects of energy production and use (air, water and thermal pollution), (iv) issues associated with energy production by nuclear fission, (v) the long-term promise of nuclear fusion as a plentiful source of clean energy, (vi) the central role of combustion in present-day energy production, and future beneficial uses of combustion (removal of toxic and hazardous materials from the environment, improvement of urban and wildland fire and explosion safety, enhancement of performance and reliability of terrestrial and space propulsion systems, production and improvement of new materials), (vii) the danger that planning in the energy area, which has a controlling effect of many other areas of planning, will be ruled by considerations which are too narrow or biased to reflect the public interest. The goals of CER are to promote interactions and solve fundamental problems in these areas, deriving from the interrelated physical, chemical, biological, engineering, economic, political and social consequences of our need for energy.

Humankind requires ever increasing acceptable sources of energy to experience a fulfilling quality of life. Energy availability plays an essential role in the overall well-being and security of the world and each of its nations. As world population and energy consumption (particularly in less-developed nations) continue to grow and concerns about global environmental impacts increase, there is a vital need for long-term, available and reliable energy supply options with attractive environmental features. Reliable energy supply is also a key issue on regional and local bases, as witnessed by the California energy crisis of 2000-2001. CER was created to foster research and educational activities devoted to critical energy needs. It provides an academic research unit for interdisciplinary interactions among UCSD faculty, research staff and students aimed at promoting and coordinating energy research and education. It complements academic departments of instructions and research with an emphasis on bridging the various disciplines related to energy research on campus and also provides a vehicle for developing other dimensions of energy research including energy policy, economics and ecology.

An overall goal of CER is to continue to be internationally respected and nationally recognized as a center of excellence in energy research as well as the leading center of energy expertise in Southern California. Current research areas emphasize plasma and fusion energy sciences, fundamental and applied combustion science and selected topics in alternative energy technologies and in energy policy issues. Future expansion is planned especially in these latter areas.

The specific objectives of CER are to:

- Advance the knowledge needed to develop essential environmentally friendly and reliable energy alternatives.
- Provide an interdepartmental coordinating function for energy research groups and projects at UCSD.
- Enhance the prospects of extramural research funding involving interdepartmental and multi-disciplinary collaborations in energy research.
- Promote the visibility of energy topics in undergraduate and graduate programs at UCSD.
- Provide a mechanism for interacting with other institutions involved in energy research, with particular attention to potential industrial partners.

- Promote the visibility of energy research at UCSD to potential sponsors and funding agencies.

2. HISTORY OF THE ENERGY CENTER

The UCSD Energy Center commenced operation informally during the fall of 1972 under the impetus of Professor Sanford S. Penner. Formally designated as an organized research unit on July 1, 1974, the Energy Center addressed application foci that varied in response to university needs. This center was given a new name, the Center for Energy and Combustion Research (CECR), in 1986, to underscore the close link between energy and combustion research. Professor Forman A. Williams, whose research specialty is combustion, succeeded S.S. Penner as Director in 1990. On July 1, 2000, the center combined with the Fusion Energy Research Program and the Virtual Laboratory for Technology at UCSD and again changed its name, to the present name, the Center for Energy Research (CER), deemed appropriate because of the relationship of both combustion and fusion to energy. It was logical to combine these different energy-related activities on campus into a single center, forming a basis for expanding thrust directions in energy.

Since its origins, the center has focused on basic problems in finding new sources of energy and the social, environmental, economic and political consequences of energy consumption as well as scientific and technological aspects of improvement in energy availability, conservation and environmental friendliness, more recently through combustion and fusion. Studies range from investigations into the fundamental nature of energy, combustion and fusion to practical applications in energy conservation and production, as well as pollution control. Today, under the direction of Professor Williams, CER exists to further basic scientific understanding and wide-ranging applications of energy resources, including both fossil and non-fossil fuels. There are investigations related to the containment of fusion processes in nuclear energy and to reduction of emissions of greenhouse gases in combustion processes.

In the combustion area, studies are in progress concerning minimization of emissions of soot and oxides of nitrogen from flames of both gaseous and liquid fuels, including sprays related to the types used in Diesel and gas-turbine engines, as well as gaseous fuels related to those used in systems employing natural gas. Advanced in-situ diagnostics are under development to assist in the study of combustion physics and reduction of emissions. There are also investigations of the stability of combustion in various types of combustion chambers and use of detonation for propulsion applications, for example, applying the strong CER expertise in fluid mechanics, reacting flows and turbulent combustion. In addition, there are fundamental studies in microgravity combustion science, involving droplet-burning experiments in Spacelab, in the International Space Station and in other NASA facilities.

In the fusion area, there are extensive and detailed studies of fusion energy systems, boundary and plasma-material interaction phenomena in magnetic plasma confinement, and experimental and theoretical investigations of laser-plasma-materials interactions, essential if inertial confinement of fusion is to become a practical reality. The Department of Energy (DOE) supports about $30M of activities in fusion technology and materials, and the United States is in negotiations to rejoin the International Thermonuclear Experimental Reactor (ITER) consortium, which currently is reviewing sites for construction of the reactor. The Virtual Laboratory for Technology (VLT) in CER coordinates these DOE activities and offers technical advice on the role of the United States in ITER.

CER exists for bringing together faculty, researchers and students from across a broad range of disciplines: applied mathematics, physics, chemistry, oceanography, meteorology and economics, as well as mechanical, aerospace, electrical, structural and chemical engineering. Experimental, analytical and computational research methods are used to study physical and chemical aspects of fusion and combustion phenomena. Collaborative study of problems using all three of these basic methods is a particular characteristic of the center.

At the societal level, during the last five years CER has published in its newsletter articles on the California energy crisis, on oil prices and the strategic oil reserves of the United States, and on the country's fusion program, for example, and it has arranged local and international conferences in both combustion and fusion. Outreach activities have extended to spreading knowledge about fusion and rocket propulsion to high school students and teachers and to the general public. Interactions with industry included research relationships with General Atomics and with Solar Turbine and Sunstrand. The principal sources of support for CER activities have been agencies of the federal government, namely DOE, NASA, NSF and DOD.

3. ACCOMPLISHMENTS SINCE THE PREVIOUS FIVE-YEAR REPORT

The most recent five-year report was the CECR report covering the period of July 1, 1989 – June 30, 1995. The name change and addition of the fusion component occurred on July 1, 2000. For these reasons, the present report summarizes the energy and combustion-area accomplishments from 1996 to the present and the fusion-area accomplishments from 2000 to the present. This same restriction is applied to the publications listed in Section 12.

a. Combustion Research

In combustion research there have been significant accomplishments in advancing understanding of fundamental combustion phenomena. Details of these accomplishments appear in the publications in the combustion area, more than 100 of which are listed in Section 12. This large number of publications reflects the wide range of accomplishments. The PhD theses, listed in Sections 12, further highlight many of these accomplishments.

We have clarified the structures of a number of different laminar flames through laboratory measurements, flame-structure computations and theoretical analyses based on asymptotic methods. These include flames of both gaseous and liquid fuels, notably hydrogen, methane (the principal component of natural gas), ethane, acetelyne, methanol and heptane, among other fuels. In comparing computational and experimental results, differences were encountered that were traceable to inaccurate selections of rate parameters for certain elementary reaction steps in the literature. These selections were improved and are now available to the research and application community through our web site. Our detailed combustion mechanism, increasingly referred to as San Diego Mech, is more successful in predicting flame structures than many other available mechanisms, a number of which are much larger and more difficult to implement. The development and dissemination of San Diego Mech is a major accomplishment during the past five years.

A novel approach to aerospace propulsion is to employ repeated detonations to produce thrust on a vehicle in flight. This concept for design of an engine, called a pulse-detonation engine, has not resulted in a practical engine because of insufficient knowledge of how best to inject and distribute fuel cyclically in a controlled manner, ignite it, form a detonation, exhaust the products and ingest air in high-speed flight. CER headed a Navy-sponsored Multidisciplinary University Research Initiative (MURI) to address these problems. As a result of the research performed in this MURI, which was recently completed, the basis now exists for efficient design of pulse-detonation engines. The Air Force plans to run flight tests of such an engine in the California desert soon.

Combustion research in CER developed information that can be used in relation to mitigation of air pollution in a number of ways. Mechanisms of production of oxides of nitrogen in flames were determined, providing knowledge needed to address measures for reduction of emissions. Knowledge of mechanisms for destruction of toxic materials also was advanced. Under the terms of the Montreal protocol brominated fluorocarbons such as CF_3Br, which are useful fire suppressants, can no longer be produced because of their detrimental role in destruction of stratospheric ozone. Research in CER revealed the chemical inhibition mechanism of CF_3Br and helped to identify possible useful replacements for these fire suppressants that could become comparably effective without producing atmospheric degradation.

A mission of NASA is to investigate benefits of human exploration and development of space. There was CER participation in studies of how best to do this and of the difficulties that may be involved. Improved knowledge of combustion of fuel droplets and sprays, applicable to combustion advancements both in space and on earth, may be obtained from gravity-free experiments on droplet combustion performed by astronauts in space. Such experiments were designed by CER and run in a laboratory on the Space Shuttle. The results of the experiments were analyzed at CER and employed in designing new experiments, planned to be performed in the International Space Station.

b. Fusion Research

In fusion research in CER at UCSD there have been major accomplishment in plasma-material interactions, experimental plasma confinement research, plasma theory, advanced energy systems analysis and inertial fusion energy/laser interactions research. Please also see the publications in Section 12. In addition, the CER conducts collaborative research at several magnetic-confinement fusion devices, including the DIII-D National Fusion Facility (DIII-D), located at General Atomics in La Jolla, California and the National Spherical Tokamak Experiment (NSTX), located at the Princeton Plasma Physics Laboratory in Princeton, New Jersey. These collaborations address critical issues for the next generation of fusion experiments related to the transport of particles, energy and radiation across the plasma to the walls of the device.

A major CER thrust is the well-known PISCES Research Program, which is focused on understanding the physics of the interaction between fusion plasmas and the materials at the plasma boundary or wall. PISCES has become a standard acronym for what originally was termed the Plasma Interaction Surface Component Experimental Station. The PISCES research consists of both basic scientific research on the nature of the boundary plasma and its interaction with materials and applied science research aimed at developing the understanding of plasma behavior and surface materials responses that is needed to support present-day and future fusion experiments. The PISCES facilities enable wind-tunnel-like simulation experiments be performed to examine materials of interest for future fusion experiments. For example, large-scale fusion experiments such as the proposed ITER facility make use of PISCES simulation data to validate key design elements including the choice of surface materials. There are two PISCES facilities, the larger and newer of which is unique in its ability to handle beryllium materials safely, enabling us to study plasma interactions with beryllium, carbon and tungsten materials that are under consideration for use in ITER.

Experiments in PISCES facilities in collaboration with US and European laboratories recently investigated the influence of beryllium impurities on deuterium plasma erosion of graphite material. These experiments are designed to reduce uncertainties in the prediction of tritium retention in redeposited mixed-materials expected in future burning plasma devices. The results will be helpful in future designs.

Experiments in PISCES also measured an increased erosion rate of both solid and liquid surfaces, exceeding that predicted by a summation of the physical sputtering rate and the thermodynamic sublimation/evaporation rate. A model based on the creation of surface adatoms by energetic projectile bombardment and subsequent adatom sublimation was developed to explain the enhanced erosion. Molecular-dynamics simulations of beryllium confirm that the experimentally measured evaporation energy is consistent with the binding energy of adatoms, supporting the new model.

The deuterium recycling properties of liquid lithium surfaces exposed to energetic, high-flux plasma bombardment also were investigated in the PISCES facilities. Low recycling of the incident ion flux in a confinement device leads to a reduction in energy lost in the edge plasma to ionization and excitation of the recycling neutrals; therefore an increase in edge-plasma temperature is expected. Lithium's low hydrogen recycling properties were demonstrated experimentally over a range of liquid temperature and incident plasma parameters, thereby increasing our understanding of potential future beneficial roles of lithium in magnetic plasma confinement devices.

In the collaboration between UCSD and NSTX, a fast-scanning probe was developed and put into operation between 2000 and 2002. The probe has twelve tips to measure a variety of plasma properties, including temperature, density and various electric fields and their fluctuations. It was installed and commissioned in the spherical tokamak at NSTX in 2002, and its first measurements were obtained that summer. The probe is helping to clarify the physics of the plasma edge, especially the scrape-off layer where higher-density impurities are removed, which critically influences tokamak operation.

In the DIII-D collaboration, CER scientists developed a method to reduce damage to plasma-facing surfaces during a disruption, an event in which large amounts of thermal energy stored in the plasma and the magnetic field are quickly converted into high power fluxes that generate large and destructive mechanical forces. This novel technique involves detecting signs of the beginning of a disruption and rapidly injecting a massive gas jet to mitigate substantially the high heat fluxes and mechanical forces. It holds promise for controlling a critical issue of next-generation fusion experiments.

After plasma pressure and current gradients increase to the limit imposed by magnetohydrodynamic instabilities, a steady state is established through cyclic relaxations of the edge plasma profiles, called edge localization modes (ELMs), which expel up to ten percent of the plasma thermal energy on very fast time scales and can erode plasma-facing surfaces. A single ELM is predicted to destroy the surface of a fusion device that produces net power. In the DIII-D cooperation, chaotic behavior of magnetic field lines was induced experimentally, significantly reducing ELM effects.

A number of advances in understanding were made concerning turbulence-related phenomena in plasmas. Although transport by microturbulence removes energy from the plasma, above a threshold amount of applied heating power the plasma spontaneously self-organizes into a state with lower turbulence levels, improving energy confinement through a process, recently explained in CER, in which turbulence energy is converted into shear flow by turbulent Reynolds stresses, much like processes that drive organization of planetary fluids into structures such as the jet stream and ocean currents on Earth and the banding of the Jovian atmosphere. Although heat conduction along magnetic field lines is the primary path of energy leaving the plasma periphery, cross-field transport of energy and particles is not negligible. Long believed to result from collisional diffusion, this cross-field transport was instead found to occur in intermittent bursts, and a theory was developed at CER to explain this in terms of coherent structures (blobs) that separate from the core plasma and propagate outward at speeds on the order of a kilometer per second. This "blobby" transport was incorporated into a transport code which then indicated that it plays a dominant role in tokamak edges and is critically important for the ITER design.

In relationship to inertial fusion, advances were made in development of optics (mirrors) for high-average-power lasers, in investigation of the behavior of armor of inertial fusion chambers under intense energy burst of inertial fusion pellets, in gas-dynamic simulation of inertial fusion chambers after the pellet explosion and in determining the evolution of cryogenic pellets during their injection into inertial-fusion chambers. Fundamental research in laser/matter and laser/plasma interaction also was vigorously pursued and has applications in other fields, ranging from nano-technology to laser-assisted manufacturing. Work has begun on a UC Discovery grant to explore development of light sources for ultraviolet lithography.

There is a fusion-area national team on Advanced Reactor Innovation and Evaluation Studies (ARIES), which performs extensive systems studies to identify not just the most effective experiments in the short term, but also the most cost-effective routes to the long-term evolution of the experimental, scientific and technological program. ARIES is funded by DOE and led by CER, which is considered the world leader in this area of research. The ARIES studies typically include a dozen other institutions — other universities, national laboratories and industry. ARIES studies have had major impact on the direction of fusion research in the U.S. and worldwide.

c. Energy Analysis

There were a number of CER accomplishments in energy analysis during this reporting period. Studies were made of California's energy history, including planning, accomplishments and identification of issues that need to be addressed. Discussion sessions and seminars were organized during and after the California energy crisis, addressing effects of deregulation and capabilities of the state. The evolution of world energy usage of different resources was analyzed, with projections made for the future. Studies of the hydrogen economy and of the future of the U.S. fusion program were performed. Results were made available in various publications and public lectures.

d. Information Dissemination and Hosting Meetings

During the reporting period, CER initiated a newsletter that is distributed electronically and in hard copy to a list of interested recipients. The Appendix to this report contains a sample of the newsletter. The CER Newsletter is also made available on the CER website. More detailed scientific and technical information in the combustion and fusion areas is published in peer-reviewed journals. CER also arranged meetings in these specialties. For example, Professor Seshadri hosted a meeting of the Western States Section of the Combustion Institute at UCSD; Professor Williams, co-chairing with Professor Troe of Germany, arranged the program of the Twenty-Ninth International Combustion Symposium, held in Sapporo, Japan; Professor Krasheninnikov hosted a four-day workshop on Plasma Edge Theory in Fusion Devices at UCSD; and Professor Baker hosted the Sixth International Symposium on Fusion Nuclear Technology, held in San Diego, CA. CER also hosted many seminars at UCSD, in these specialties as well as on more general topics related to energy as listed in Section 11.

e. Education and Outreach

There were a variety of education and outreach accomplishments by CER during this reporting period. Faculty in CER regularly taught MAE undergraduate and graduate courses related to energy in the Department of Mechanical and Aerospace Engineering (MAE) as well as courses in the chemical engineering program (CENG courses). In addition, CER personnel taught special seminar courses at UCSD, taken mainly by high school students. One of these, in the combustion area, entitled “Rocket Propulsion”, addressed basic principles of rocket propulsion at a high-school level. A related activity, in the fusion area, was the “Summer Plasma Institute”, which is attended by undergraduate students from several participating institutions and is given each year; this course is designed to encourage undergraduate students to consider careers in plasma physics. CER also participated in the STARS program (Summer Training Academy for Research in the Sciences), which attempts to increase the number of undergraduate students who go on to doctoral programs in science by involving them in laboratory experiments early in their studies. The website for the Virtual Laboratory for Technology has maintained fusion information readily accessible to the public.

The Center for Energy Research supported K-12 educational outreach activities with several efforts designed to interest K-12 students in careers in physics and energy-related fields. One such activity is a yearly outreach program held in conjunction with the annual meeting of the American Physical Society (APS) Division of Plasma Physics. High school and middle school teachers from the area in which the APS meeting is held are invited to participate in a day-long series of workshops designed especially for them, at which scientists from participating institutions present topics in plasmas and fusion science, fluid instabilities, the electromagnetic spectrum, radioactivity and the nature of matter. CER scientists are active participants in this activity. At the same APS meeting there is a Plasma Expo, a two-day presentation of hands-on activities in plasma science and technology which follows the teachers' workshops. At Plasma Expo, CER has two large, interactive displays with various experiments and demonstrations in which students and teachers can participate. These activities have met with great enthusiasm by the students and teachers in attendance.

f. International Interactions

Strong international ties are maintained by CER. There are many ongoing joint research projects with foreign scientists in the combustion and fusion areas. These include collaborations in both Europe and Asia, notably Germany, France, Spain and Japan. Foreign visitors are hosted by CER for periods of research extending from one month to two years, and researchers from CER regularly spend brief or extended periods abroad furthering the research objectives. Each August, there is a CER summer seminar series in the combustion area, at which foreign visitors present their research results. Faculty in CER arrange for international meetings and present invited lectures abroad. For example, Professor S.S. Penner gave invited lectures on "Long-Term Energy Supplies for the World" and on "Fuel Cells for Transportation Vehicles" at Porto Venere Conferences on Energy, Ecology and Economy in Italy.

4. SUMMARY OF VALUE OF CER TO UCSD AND RATIONALIZATION FOR CONTINUATION

The campus benefits from the presence of CER in a number of ways:

- The Center provides a forum for addressing and discussing energy-related issues which in the future in California are likely to become of critical concern from time to time, as they have in the past.
- The Center contributes to the visibility of the campus in the energy area at local and statewide levels.

- The Center enhances the national and international reputation of UCSD in the areas of combustion and fusion research.

- The Center increases the likelihood of winning substantial extramural funding at UCSD for multidisciplinary energy-related research.

- The Center engages in outreach activities and offers educational opportunities to undergraduate, graduate and post-doctoral students at UCSD in energy-related areas.

- Research performed in the Center advances knowledge that is needed for developing reliable, efficient and environmentally friendly energy alternatives.

- The Center provides a mechanism for interacting with other institutions, industrial partners and other departments on campus in energy-related studies and research.

The facts underpinning the rationale for continuing the Center are the following:

- The Center is positioned to address pressing energy problems as they arise in the future.

- The Center brings together different groups on campus having interest in energy, groups which otherwise would not work together.

- The Center is in a growth mode, with increasing funding and personnel.

- The mission of the Center, as summarized in the mission statement, is an important one that is not addressed elsewhere on campus and that is likely to become of increasing interest in the future.

- CER is a lively organization with vigorous and growing research and educational activities on a number of fronts, offering excelled promise of important future contributions.

In general, organizations can become stagnant and complacent after a period of time, ceasing to evolve and to contribute significantly. Such organizations are rightly terminated in a sunset review. CER is, however, the antithesis of such organizations. It is evolving and expanding vigorously and therefore deserves continuation. Energy considerations surely will be prominent among societal concerns in the future.

5. TEACHING AND EDUCATIONAL ACTIVITES, PRESENT AND FUTURE

The CER teaching activities are closely coordinated with research. Graduate students are involved in theoretical, computational and experimental work associated with the specific topics of research identified above, and the most thorough and definitive presentation of results often appears in the theses of graduate students. Undergraduate students also participate in the laboratory research. For the reporting period, the following UCSD undergraduates were involved in CER laboratory studies:

Sophia Chen
Calvin Chou
PapaMagatte Diagne
Joshua Hu
Jeremy Livianu
Maria Liza Lopez
Donaldi Luca
Eugene Mahmoud
Adrian Mansbridge
Pavel Monat
Sailendra Nemana
Steve Phan
Christopher Romero
Jeffrey Robert Scherffius
Caitlin Smythe
Joshua Tyndall
Werner Willems
Brandon York

The teaching involves extensive individual contacts of students with professors and research staff. In today's rapidly changing world, there is need for disciplinary flexibility and international exposure in education. The students associated with CER achieve this through contacts and travels outside UCSD. Students and researchers associated with universities throughout the U.S. and the world spend periods of time in research at CER, and UCSD students in CER often pursue part of their thesis research at these external institutions. The cooperation provides an important broadening of perspective.

Formal courses of instruction are associated with CER at both the undergraduate and graduate levels in the MAE and ECE departments. An undergraduate seminar on Energy Options for the Twenty-First Century was recently initiated. There is a four-quarter undergraduate sequence in energy, covering thermodynamics, energy from fossil fuels, nuclear fission energy and nuclear fusion energy. Enrollments are typically around fifty students per course per year. A larger number of graduate courses are given in the discipline areas of fluid mechanics, gas dynamics, heat and mass transfer, combustion, propulsion, turbulence, numerical and mathematical methods, and plasma science and engineering. These courses are taken by most of the graduate students in CER. There are, in addition, a number of CER seminars, including a regular summer seminar series and different special seminar series throughout the year. By attending these seminars students extend their knowledge outside their immediate area of specialization. All of these educational activities rely strongly on CER. For example, even though the undergraduate courses are within specific academic departments, their vitality, motivation and high ratings are largely attributable to CER.

In the future, expansion of these teaching programs would occur in connection with the proposed expansion of CER. If, for example, an appointment in energy policy was made, then additional seminars and courses would be instituted. The extenMaded teaching activity would apply strongly at the graduate level and would greatly increase the cross-disciplinary components of CER, leading to beneficial influences on a wider range of societal endeavors. There would, however, also be additional courses instituted at the undergraduate level to accommodate increasing undergraduate enrollment.

Independent of future expansion, plans are underway to introduce new undergraduate and graduate courses in combustion, fusion and energy. This is deemed necessary because of increasing student enrollment. For example, plans are developing for revision and expansion of the undergraduate energy sequence and consideration is being given to an undergraduate course and an additional graduate course in combustion.

6. INTERACTION WITH OTHER UNITS, PRESENT AND FUTURE

Energy research is by its very nature a multidisciplinary research endeavor. Such research not only offers many opportunities for collaborative work across many disciplines, but it requires such an approach to be successful. CER brings together faculty, researchers and students from across a broad range of disciplines: applied mathematics, physics, chemistry, oceanography, meteorology and economics, as well as mechanical, aerospace, civil and chemical engineering. At present, the vast majority of faculty, research staff and students come from MAE, although a sizable minority come from ECE. There are also interactions with the Program in Chemical Engineering and with the Graduate Program in Materials Science. There are affiliated faculty in the departments of Physics and Chemistry and Biochemistry (see Section 9). Experimental, analytical and computational research methods are used to study chemical and physical aspects of combustion and fusion phenomena. There is also interest in pursuing more general energy studies on an interdepartmental basis. Research topics are selected which foster multidisciplinary approaches. For example, there is a particularly strong connection with environmental research at UCSD.

There is need to expand CER activities, to add to its internationally recognized plasma/fusion research and fundamental combustion research augmented components that are more active in renewable energy, environmental effects and energy and environmental policy. This expansion would enhance the interdisciplinary character of CER beyond the Jacobs School of Engineering to include, for example, elements in IRPS, SIO, the San Diego Supercomputer Center and the Departments of Economics, Mathematics, Physics, and Chemistry and Biochemistry. See Section 16 for further discussion of expansion.

7. PUBLIC SERVICE ACTIVITIES, PRESENT AND FUTURE

CER maintains a number of public service activities. Among these is offering advice to federal, state and local governments on energy-related issues. For example, there are advisory services in fire safety to the National Construction Safety Team, in fusion research to DOE through the ARIES project, to NASA on directions in combustion research through the Microgravity Combustion Working Group and to the California Air Resources Board through its Research Screening Committee. CER personnel arrange for and host scientific and technical meetings in fusion and combustion areas and serve on editorial advisory committees of leading journals in their fields, as well as reviewing proposals and papers submitted for publication and editing special issues of journals. Seminars hosted by CER in fusion, combustion and energy are open to the public. Presentations and exhibits by CER at technical meetings are often directed to the public and to high school students and teachers. Direction to scientific organizations is provided through membership on boards of directors and on technical committees. Finally, articles evaluating current energy problems are distributed, for example, through the CER website and newsletter.

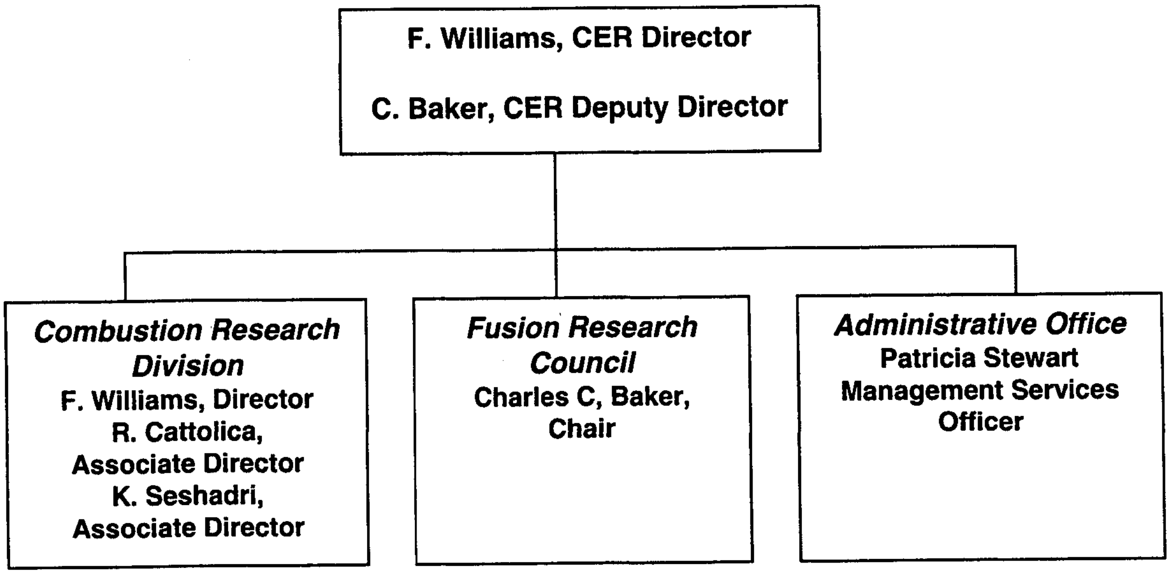
These public service activities are planned to continue in the future. In addition, new activities of this kind are planned if the proposed expansion into Alternative Energy Technologies and Energy Assessments comes to pass (see Section 16). Strengthening these areas would increase publications and activities offering advice to the public and governments on a wider range of energy issues.

8. ORGANIZATION AND ADMINISTRATION OF CER

Professor Forman A. Williams of MAE is Director of CER with Dr. Charles C. Baker, Adjunct Professor of MAE and Director of the Virtual Laboratory for Technology, serving as Deputy Director. The organizational chart for the administration of the CER is shown in Figure 1.

The CER has established an internal Executive Committee consisting of faculty and senior research staff of the Center. Members of the Executive Committee are: Charles C. Baker, Chair, Professor Robert Cattolica (MAE), Professor Sergei Krasheninnikov (MAE), Dr. Stan Luckhardt (MAE), Professor Farrokh Najmabadi (ECE), Professor Kalyanasundaram Seshadri (MAE), and Professor George Tynan (MAE).

Figure 1. CER Organizational Chart



9. PRESENT PERSONNEL OF CER

a. Faculty

i. Members

- **Charles Baker, Adjunct Professor/MAE:** Fusion systems analysis; fusion nuclear technology development; plasma engineering.
- **Farhat Beg, Assistant Professor/MAE:** Fast ignition for inertial confinement fusion; wire array Z-pinches; compact x-ray and neutron sources.
- **Steven Buckley, Assistant Professor/MAE:** Combustion physics; in-situ combustion and atmospheric emission measurement techniques; gas-phase, particulate-phase and bio-aerosol measurements.
- **Robert Cattolica, Professor/MAE**: Laser and electron beam spectroscopic diagnostics; molecular energy transfer; combustion and hypersonic gas dynamics.

- **Robert Conn, Professor/MAE:** Applied plasma physics and technology; fusion energy; fusion reactor design; methods for semiconductor etching and deposition processes; plasma chemistry; applied chemical physics.
- **Sergei Krasheninnikov, Professor/MAE**: Plasma, neutral, and radiation interactions and transport phenomena; plasma turbulence; atomic physics in plasmas; plasma-material interactions; gas discharge physics; plasma chemistry.
- **Paul Libby, Professor Emeritus/MAE**: Combustion theory; turbulence; turbulent combustion.
- **Farrokh Najmabadi, Professor/ECE:** Fusion power plant design and technology; computational fluid dynamics; laser-material interaction; applied plasma physics and engineering.
- **Stanford Penner, Professor Emeritus/MAE**: Thermophysics; applied spectroscopy; propellants; energy technologies; environmental issues - management and policies.
- **K. Seshadri, Professor/MAE**: Chemical inhibition of flames; combustion of diesel fuels; combustion of solid propellants; mechanisms of formation of pollutants; destruction of toxic compounds; asymptotic analyses of flame structure.
- **George Tynan, Associate Professor/MAE:** Interaction of high-energy-density radio frequency with edge plasmas in magnetic fusion devices; fundamental studies of intense laser-plasma interactions; turbulent transport in magnetized plasmas; physics of semiconductor process plasmas.
- **Forman Williams, Professor/MAE:** Flame theory, combustion in turbulent flows, asymptotic methods in combustion, fire research, reactions in boundary layers, other areas of combustion and fluid dynamics.

ii. Faculty Affiliates

- **David Benson, Professor/MAE**: Development of algorithms for nonlinear finite element analysis on supercomputers.
- **Thomas Bewley, Assistant Professor/MAE**: Control, forecasting, and optimization of laminar and turbulent flows.
- **Colm Caulfield, Associate Professor/MAE:** Fluid flows in the environment, industry and geophysics where density or compositional differences play a crucial dynamical role.
- **Pat Diamond, Professor/Physics:** Turbulence, transport and self-organization in plasmas, fluids and nonequilibrium systems; bifurcated mean-flow states in turbulent shear flows; magnetic dynamics; confinement and turbulence in magnetized plasmas; anomalous viscosity mechanisms in accretion disks; flows in granular media.

- **Miroslav Krstic, Professor/MAE**: Adaptive, and robust control theory, dynamical system theory.
- **Juan Lasheras, Professor/MAE:** Turbulent flows, two-phase flows and bio-fluid mechanics; laboratory and mathematical modeling of flows relevant to a wide range of applications.
- **Paul Linden, Professor, MAE:** Laboratory and theoretical modeling of flows in the disciplines of geophysical, environmental and industrial fluid dynamics.
- **Marc Meyers, Professor/MAE**: Dynamic behavior of materials; shock-wave effects; dynamic fracture by spalling and fragmentation; adiabatic shear localization; solid-phase transformations; shock-induced and shear-induced chemical reactions.
- **David Miller, Professor/MAE**: Engineering physics, especially related to experimental molecular-beam experiments; gas dynamics of free-jet expansions; gas-surface interactions; chemistry in supercritical fluids.
- **Vitali Nesterenko, Professor/MAE:** Micromechanics of powder deformation under dynamic and quasistatic loading; shear instability in heterogeneous materials under dynamic loading; shear-induced chemical reactions in condensed materials; wave propagation.
- **Keiko Nomura, Associate Professor/MAE**: Theoretical and computational fluid mechanics, turbulence, transport phenomena, reacting flows and combustion; environmental flows.
- **Tom O'Neil, Professor/Physics:** Theoretical plasma physics; transport, turbulence and relaxation phenomena in nonneutral plasmas; atomic processes involving loosely bound charged particles.
- **Kim Prather, Professor/Chemistry and Biochemistry:** Laboratory and field studies of rapid sizing and chemical characterization of environmentally important aerosol particles by mass spectrometry and related techniques.
- **Sutanu Sarkar, Associate Professor/MAE**: Simulation and modeling of turbulence in high-speed flows, reacting flows and stratified environmental flows.

b. Research Scientists

- **Ghassan Antar, Assistant Research Scientist** : Turbulence and transport.
- **Matthew Baldwin, Assistant Research Scientist:** Plasma materials interactions.
- **José Boedo, Research Scientist:** Causes and effects of plasma convection on the edge and scrape-off layer of fusion plasmas, particularly divertors.

- **Russ Doerner, Research Scientist:** Experimental studies of plasma-materials interactions and boundary-layer plasma physics.
- **Zoran Dragojlovic, Assistant Project Scientist**: Numerical and experimental fluid mechanics with heat and mass transfer.
- **Andreas Gaeris, Assistant Project Scientist**: Radiation processes and nonlinear waves in plasmas; shock physics in condensed matter and fluids; space plasmas.
- **S. S. Harilal, Assistant Project Scientist**: Laser and plasma spectroscopy; laser plasma x-ray sources; laser-matter interaction; colliding plasmas; plasma spectroscopy.
- **Stan Luckhardt, Research Scientist:** Fundamental studies of plasma flow phenomena; fluctuations and wave-particle interactions in laboratory plasmas with applications to magnetic fusion, including plasma heating and current generation and related magnetohydrodynamic equilibrium and mode behavior.
- **T. K. Mau, Research Scientist:** Radio-frequency waves in plasmas; radio-frequency heating and current drive; optical engineering.
- **Rick Moyer, Research Scientist**: Investigation of plasma turbulence and transport using Langmuir probes.
- **Alexander Pigarov, Assistant Research Scientist**: Divertor and edge physics.
- **René Raffray, Research Scientist:** Chamber engineering; ARIES fusion power plant program; fusion technology; modeling of thermal and mass transfer; thermofluid analysis and energy systems.
- **Dmitry Rudakov, Assistant Research Scientist:** Experimental boundary physics using reciprocating probes; edge and scrape-off layer turbulence and transport; edge-transport barrier formation; H-mode physics; studies of edge localized modes; divertor physics.
- **Reinhard Seiser, Assistant Research Scientist**: flame studies on hydrocarbon fuels and hydrogen; measurement of intermediate species, autoignition and extinction behavior; development of surrogate fuels.
- **Dai Kai Sze, Research Scientist:** US-Japan collaboration program - JUPITER-II; ITER TBM (Test-Blanket Module) studies, including molten-salt coolants, Li/V corrosion and MHD coating development; assessment of chemistry-tritium control for molten-salt fusion blankets.
- **Mark Tillack, Research Scientist:** High-energy lasers and laser-matter interactions.

c. Engineering and Technical Staff

Conley Chafin	Asst. Development Engineer
Leo Chousal	Sr. Development Engineer
Justin Delemus	EH & S Specialist
Douglas Gray	Assoc. Development Engineer
Arthur Grossman	Sr. Development Engineer
Rolando Hernandez	Assoc. Development Engineer
Jappe Hoeben	Staff Research Associate I
Stefan Humer	Staff Research Associate I
Sastry Indrakanti	Jr. Development Engineer
Joshua Lee	Staff Research Associate I
Tyler Lynch	Jr. Development Engineer
John Pulsifer	Assoc. Development Engineer
Xingping Qu	Programmer/Analyst II
Ray Seraydarian	Assoc. Development Engineer
Bruce Thomas	Asst. Development Engineer
Xueren Wang	Asst. Development Engineer
Mofreh Zaghloul	Asst. Development Engineer

d. Students and Post Graduate Researchers

Laizhong Cai	Graduate Student Researcher
Sophia Chen	Graduate Student Researcher
Brian Christensen	Graduate Student Researcher
Gonzalo Del Alamo	Graduate Student Researcher
Carlos Estrada-Mila	Graduate Student Researcher
Franscesco Ferioli	Graduate Student Researcher
Boris Frolov	Graduate Student Researcher
Andreas Gaeris	Graduate Student Researcher
Reza Gharavi	Graduate Student Researcher
Bindhu Harilal	Post Graduate Researcher
Zuhair Ibrahim	Graduate Student Researcher
Gregg Lithgow	Graduate Student Researcher
Eider Oyarzabal	Graduate Student Researcher
Maria Petrova	Graduate Student Researcher
Ali Rangwala	Graduate Student Researcher

Priyank Saxena	Graduate Student Researcher
Ariel Schuger	Graduate Student Researcher
Kevin Sequoia	Graduate Student Researcher
Masashi Shimada	Graduate Student Researcher
Tsutomo Shimizu	Graduate Student Researcher
Kurt Taylor	Graduate Student Researcher
Alexander Telengator	Post Doctoral Researcher
Zheng Yan	Graduate Student Researcher
Guanghui Yu	Graduate Student Researcher

e. Administrative Personnel

Nancy Bastian	Administrative Specialist
Claudette Hennessy	Administrative Assistant III
Ruth Lingo	Administrative Analyst
Mary Olivarria	Administrative Assistant III
Patricia Stewart	Management Services Officer
Phyllis Voigts	Administrative Specialist

10. EXTERNAL INTERACTIONS AND CER VISITORS

There are extensive external interactions of CER participants, both in this country and abroad. These interactions occur through communications by all media and through visits of CER personnel to other institutions and visits of personnel from other institutions to CER. CER also hosts a number of meetings, a few of which were mentioned in Section 3d. An indication of the extent of these external interactions is provided by the following list of visitors to CER for a period of one month or more.

DATES	VISITOR	AFFILIATION
1996	Clemens Brinkheimer	RWTH Aachen, Aachen, Germany
1996 (August)	Michel Champion	ENSMA, Poitiers, France
1996 (August)	Paul Clavin	Universite Aix Marseilles, Marseilles, France
1996 (August)	Ritsu Dobashi	The University of Tokyo, Tokyo, Japan
1996	Adelbert Grudno	RWTH Aachen, Aachen, Germany
1996 (May)	Osamu Habara	The University of Tokyo, Tokyo, Japan
1996	Øyvind Hovde	Norwegian Institute of Technology, Trondheim, Norway

DATES	VISITOR	AFFILIATION
1996	Hideaki Kobayashi	Tohoku University, Sendai, Japan
1996 (August)	Amable Liñán	Ciudad Universitaria, Madrid, Spain
1996	Akira Matsushita	Japanese Patent Office, Tokyo, Japan
1996 (May)	Masato Mikami	Yamaguchi University, Yamaguchi, Japan
1996 (August)	Norbert Peters	RWTH Aachen, Aachen, Germany
1996 (May)	Jun'ichi Sato	Ishikawajima-Harima Heavy Industries, Tokyo, Japan
1996 (August)	Juan Esteban Garcia Schafer	Universidad Politecnica de Madrid, Madrid, Spain
1996	Chae Hoon Sohn	Seoul National University, Seoul, South Korea
1996 (February)	Otto Sonju	Norwegian Institute of Technology, Trondheim, Norway
1996 (February)	Tord Peter Ursin	Norwegian Institute of Technology, Trondheim, Norway
1997	Henning Berg	Norwegian Institute of Technology, Trondheim, Norway
1997 (August)	K.N.C. Bray	Cambridge University, Cambridge, England
1997 (August)	Michel Champion	ENSMA, Poitiers, France
1997 (August)	Paul Clavin	Universite Aix Marseilles, Marseilles, France
1997 (August)	Junichi Furukawa	Tokyo Metropolitan Technical College
1997	Adelbert Grudno	RWTH Aachen, Aachen, Germany
1997	Øyvind Hovde	Norwegian Institute of Technology, Trondheim, Norway
1997 (August)	Javier Jiménez	Universidad Politecnica de Madrid
1997	Haaidong Li	The Technion, Israel
1997 (August)	Amable Liñán	Ciudad Universitaria, Madrid, Spain
1997 (February)	Masato Mikami	Yamaguchi University, Yamaguchi, Japan
1997 (February)	Keiichi Okai	The University of Tokyo, Tokyo, Japan
1997	Heinz Pitsch	RWTH Aachen, Aachen, Germany
1997	Geir Roertviet	Norwegian Institute of Technology, Trondheim, Norway
1997 (August)	Antonio Sanchez	Universidad Carlos III, Madrid, Spain
1997	Reinhard Seiser	Technical University, Graz, Austria
1997	Ingrid Smedvig	Norwegian Institute of Technology, Trondheim, Norway
1998 (August)	K.N.C. Bray	Cambridge University, Cambridge, England
1998 (August)	Michel Champion	ENSMA, Poitiers, France
1998 (August)	Paul Clavin	Universite Aix Marseilles, Marseilles, France
1998	Fernando Fachini	Instituto Nacional de Pesquisas Espaciais - INPE, Brazil
1998 (October)	Junichi Furukawa	Tokyo Metropolitan Technical College
1998 (August)	Amable Liñán	Ciudad Universitaria, Madrid, Spain
1998 (April)	Keiichi Okai	The University of Tokyo, Tokyo, Japan
1998	Heinz Pitsch	RWTH Aachen, Aachen, Germany
1998 (August)	Antonio Luis Sánchez	Universidad Carlos III, Madrid, Spain
1998	Reinhard Seiser	Technical University, Graz, Austria

DATES	VISITOR	AFFILIATION
1999 (August)	K.N.C. Bray	Cambridge University, Cambridge, England
1999	Dag Brevik	Norwegian Univ. of Science and Tech., Trondheim, Norway
1999 (August)	Michel Champion	ENSMA, Futuroscope, France
1999 (August)	Paul Clavin	CNRS - Universités d'Aix-Marseilles, Marseilles, France
1999	Knut Harald Lien	Norwegian Univ. of Science and Tech., Trondheim, Norway
1999 (August)	Amable Liñán	Universidad Politécnica de Madrid, Madrid, Spain
1999	Hideaki Kobayashi	Tohoku University, Miyagi, Japan
1999 (February)	Keiichi Okai	The University of Tokyo, Tokyo, Japan
1999 (August)	Jose Graña Otero	Universidad Politécnica de Madrid, Madrid, Spain
1999 (July)	Norbert Peters	Institut fuer Technische Mechanik, RWTH Aachen, Germany
1999	Jan Petter Pettersen	Norwegian Univ. of Science and Tech., Trondheim, Norway
1999 (July)	Heinz Pitsch	Institut fuer Technische Mechanik, RWTH Aachen, Germany
1999	Geir Roertveit	Norwegian Univ. of Science and Tech., Trondheim, Norway
1999	Oystein Skiri	Norwegian Univ. of Science and Tech., Trondheim, Norway
1999 (August)	Antonio Luis Sanchez	Universidad Carlos III de Madrid, Madrid, Spain
2000	Michael Booty	New Jersey Institute of Technology, Newark, New Jersey
2000 (August)	K.N.C. Bray	Cambridge University, Cambridge, England
2000	Dag Brevik	Norwegian Univ. of Science and Tech., Trondheim, Norway
2000	Stine Carlsen	Norwegian Univ. of Science and Tech., Trondheim, Norway
2000 (August)	Michel Champion	ENSMA, Futuroscope, France
2000 (March)	Junichi Furukawa	Tokyo Metropolitan Technical College, Tokyo, Japan
2000 (August)	Amable Liñán	Universidad Politécnica de Madrid, Madrid, Spain
2000	Jan Petter Pettersen	Norwegian Univ. of Science and Tech., Trondheim, Norway
2000	Edgar Piskernik	Technical University Graz, Austria
2000 (November)	Chung Wu	IPP Garching, Germany
2000	Shenqyang Shy	National Central University, Taiwan, R.O.C.
2000 (August)	José-Manuel Vega	Universidad Politécnica de Madrid, Madrid, Spain

DATES	VISITOR	AFFILIATION
2001 (August)	K.N.C. Bray	Cambridge University, Cambridge, England
2001 (August)	Michel Champion	ENSMA, Futuroscope, France
2001 (August)	Paul Clavin	CNRS - Universités d'Aix-Marseilles, Marseilles, France
2001 (August)	Marcos Vera Coello	Universidad Politécnica de Madrid, Madrid, Spain
2001 (December)	Bruno Coppi	Mass. Institute of Technology
2001	John H.S. Lee	McGill University
2001 (August)	Amable Liñán	Universidad Politécnica de Madrid, Madrid, Spain
2001 (January)	Keiichi Okia	University of Tokyo
2001 (August)	Antonio Revuelta	Universidad Carlos III de Madrid
2001 (August)	Antonio Sanchez	Universidad Carlos III de Madrid
2001 (November)	Michael Shats	Australian National University
2001 (May)	Ralf Schneider	IPP Greifwald, Germany
2001 (January)	Takeshi Ueda	University of Tokyo
2001 (November)	Chung Wu	IPP Garching, Germany
2002 (December)	Kim Arkady	Chalmers Institute of Technology, Sweden
2002	Merete Bing-Jacobsen	Norwegian Institute of Technology
2002 (August)	K.N.C. Bray	Cambridge University, Cambridge, England
2002 (August)	Michel Champion	ENSMA, Futuroscope, France
2002 (August)	Paul Clavin	CNRS - Universités d'Aix-Marseilles, Marseilles, France
2002 (August)	Marcos Vera Coello	Universidad Politécnica de Madrid, Madrid, Spain
2002 (October)	Jill Dahlburg	General Atomics, San Diego
2002 (November)	Junichi Furukawa	Tokyo Metropolitan College of Technology
2002 (March)	Valery Godyak	OSRAM Sylvania
2002	Stefan Humer	Vienna University of Technology, Austria
2002	Marianne Jensen	Norwegian Institute of Technology
2002 (December)	Boris Khripunov	Kurchatov Institute, Russia
2002 (March)	Andrei Kukushkin	ITER Garching Work Site, Germany
2002 (August)	Amable Liñán	Universidad Politécnica de Madrid, Madrid, Spain
2002 (December)	Alexey Muksunov	Kurchatov Institute, Russia
2002	Wolfgang Payer	Vienna University of Technology, Austria
2002 (April)	Grigori Pereverzev	IPP Garching, Germany
2002 (July)	Tatiana Soboleva	UNAM, Mexico City, Mexico
2002 (January)	Jörg Winter	Bochum University, Germany
2002 (November)	Chung Wu	IPP Garching, Germany
2003 (August)	K.N.C. Bray	Cambridge University, Cambridge, England
2003	Rion Causey	Sandia National Laboratories
2003 (August)	Michel Champion	ENSMA, Futuroscope, France

DATES	VISITOR	AFFILIATION
2003 (August)	Paul Clavin	CNRS - Universités d'Aix-Marseilles, Marseilles, France
2003	Don Cowgill	Sandia National Laboratories
2003 (August)	Marcos Vera Coello	Universidad Politécnica de Madrid, Madrid, Spain
2003 (April)	Fernando Fachini	Instituto Nacional de Pesquisas Espaciais, Brasil
2003	Maarten Gerth	Technical University of Eindhoven, Holland
2003 (August)	Miguel Hermanns	Universidad Politécnica de Madrid, Madrid, Spain
2003	Hiroshi Hirooka	NIFS, Japan
2003	Stefan Humer	Vienna University of Technology, Austria
2003	Marianne Jensen	Norwegian Institute of Technology
2003	Andreas Kirschner	KFA Jülich, Germany
2003	Aart Kleyn	Leiden Institute, Netherlands
2003	Ryoichi Kurihara	JAERI, Japan
2003 (August)	Amable Liñán	Universidad Politécnica de Madrid, Madrid, Spain
2003	Christian Linsmeier	IPP Garching, Germany
2003	Noriyasu Ohno	Nagoya University, Japan
2003	Jochen Roth	IPP Garching, Germany
2003	Takuya Saito	STA, Japan
2003	Klaus Schmidt	IPP Garching, Germany
2003 (June)	Andrei Smolyakov	University of Saskatchewan, Canada
2003	Arimichi Takayama	Nat. Insitute of Fusion Science, Japan
2003	Bill Tang	Princeton Plasma Phys. Laboratory
2003	Kimitoshi Tanoue	Oita University, Oita, Japan
2003	Kazutoshi Tokunaga	Kyushu University, Japan

11. CER SEMINARS

CER sponsors a general series of seminars and public lectures in its areas of activities. A listing of these seminars from 1996-2004 is shown below:

DATE	SPEAKER	TITLE
January 8, 1996	S.S. Penner	Commercialization of Fuel Cells
January 9, 1996	Joseph Rom	On the Acceleration of Projectiles in the In-Tube Chemical Accelerators
January 16, 1996	Massoud Simnad	The Worldwide Satus of Nuclear Energy and Nuclear Proliferation

DATE	SPEAKER	TITLE
January 22, 1996	Thomas Schneider	Impact on the Utility Industry of the Changed Environment
January 29, 1996	William Nierenberg	Global Climate Change and Fossil Fuel Utilization
February 1, 1996	A. K. Oppenheim	Inverse Problem in Combustion Revisited
February 6, 1996	Kenneth Train	Incentives for Appliance Efficiency in a Competitive Energy Industry
February 12, 1996	Anthony Sebald	The Use of Intelligent Systems for Managing Energy Conservation
February 20, 1996	Charles Baker	The Future of Fusion Energy
February 27, 1996	William Whittemore	Review of Neutron Therapy of Brain Tumors and Skin Melanomas
February 29, 1996	Ken Schultz	Inertial Fusion
March 8, 1996	Verena Moser	Large Eddy Simulation of Premixed Turbulent Combustion Using a Capturing Tracking Hybrid Scheme
March 11, 1996	K. R. Sridhar	Solid Oxide Electrolysis
April 26, 1996	Jim Riley	Modeling Subgrid-Scale Chemistry in Turbulent Reacting Flows
May 16, 1996	William Sirignano	Stability of Injected Liquids
May 30, 1996	Valentino Tiangco	Review of Biomass Energy Conversion Systems
May 30, 1996	Katja Lindenberg	Nonclassical Kinetics of Diffusion-Limited Reactions in Restricted Geometries
August 12, 1996	B. Ganeshan	Direct Numerical Simulation of Diffusion Flames with Large Heat Release in Compressible Homogeneous Turbulence
August 13, 1996	Fred Singer	The Ozone-CFC Debacle: Hasty Action, Shaky Science
August 14, 1996	Bai-Li Zhang	Theoretical Studies of Methanol Droplet Combustion Based on Results from the Shuttle Spacelab during the USML-2 Mission
August 16, 1996	Amable Liñán	Burke-Schumann Formulation for Laminar and Turbulent Diffusion Flames with Finite-Rate Recombination Chemistry

DATE	SPEAKER	TITLE
August 23, 1996	Michele Champion	Non-Gradient Diffusion in 2-D Premixed Flames
August 28, 1996	Nenad Ilincic	Modeling of Ignition of Solid-Propellant Dark Zones
September 4, 1996	Christophe Clanet	On Some Interfacial Phenomena in Liquid Jets
October 9, 1996	Yousef Bahadori	Transitional and Turbulent Jet Diffusion Flames in Microgravity
October 16, 1996	James Hill	Numerical Experiments on Turbulent Mixing with Chemical Reaction
October 23, 1996	Paul Libby	Recent Research on Premixed Flames in Stagnating Turbulence
October 30, 1996	Harry Dwyer	Some Recent Progress in the Calculation of Droplet Dynamics
November 7, 1996	Carl Meinhart	Particle-Image Velocimetry (PIV) and its Application to a Turbulent Boundary Layer
November 19, 1996	Al Turan	Predictive Modelling of Boiler Fouling
November 21, 1996	Corinne Connon	Understanding Droplet Stream Behavior under Various Conditions
December 3, 1996	Clifford Surko	Phase-Defect Description of Traveling-Wave Convection
January 30, 1997	A.K. Oppenheim	Refinement of Heat Release Analysis
February 13, 1997	Steven Buckley	Real-Time Monitoring of Toxic Metals, Chlorinated Hydrocarbons and Ammonia in Flames and Postcombustion Gases
March 31, 1997	Carl Gibson	Fluid Mechanics of Self-Gravitational Condensation: Super-Clusters, Primordial Fog, Stars and Dark-Matter
April 11, 1997	Forman A. Williams	Microgravity Combustion Studies on STS-83
April 30, 1997	Gregory T. Linteris	Combustion Experiments in Space
August 11, 1997	Jong Soo Kim	Diffusional-Thermal Instability of Diffusion Flames
August 13, 1997	Amable Liñán	Flame Spread Over Solid Fuels
August 15, 1997	Paul Clavin	Dynamics of Combustion Waves in Gases
August 20, 1997	Paul Ronney	Structures of Flame Balls At Low Lewis Number
August 25, 1997	K.N.C. Bray	Interaction Between Laminar Counterflow Flames and Water Mist
August 26, 1997	Antonio Sanchez	Chain-Branching Explosions in Mixing Layers
August 26, 1997	Paul Dimotakis	Mixing and Chemical Reactions in High-Speed Shear-Layer Flows

DATE	SPEAKER	TITLE
August 27, 1997	Michel Champion	Introduction of Dilution in the BML Model of Turbulent Combustion: Application to a Stagnating Flame
September 23, 1997	James Cole	California Institute for Energy Efficiency
December 2, 1997	Daniel Rosner	Morphological Evolution of Nano-Particles in Counterflow Diffusion Falmes - Measurements and Modeling
December 2, 1997	Misha Chertkov	Propagation of a Huygens Front Through a Turbulent Medium
January 27, 1998	Bernard J. Matkowsky	Instabilities, Fingering and the Saffman-Taylor Problem in Filtration Combustion
January 28, 1998	A.K. Oppenheim	Life of Fuel in the Course of Combustion
March 20, 1998	William T. Ashurst	Darrieus-Landau Instability, Growing Cycloids and Expanding Flame Acceleration
May 12, 1998	Howard D. Ross	Combustion on Orbiting Spacecraft and Mars
May 15, 1998	Miltiadis Papalexandris	Unsplit Shock Algorithms and their Application to the Simulation of Unstable Detonations
June 19, 1998	Heinz Pitsch	A Flamelet Formulation for Nonpremixed Combusiton Considering Differential Diffusion Effects
July 29, 1998	Jose Graña Otero	Nonsteady Flame Propagation
August 10, 1998	Paul A. Libby	An Analysis of Partially Premixed Turbulent Combustion
August 12, 1998	John Abraham	The Modeling of Diesel Sprays and Combustion
August 14, 1998	K.N.C. Bray	Premixed Turbulent Combustion: Pressure Gradients and Counter-Gradient Diffusion
August 19, 1998	Amable Liñán	The Attachment of Diffusion Flames in the Near Wake of Fuel Injectors
August 21, 1998	Paul Ronney	Diffusive-Thermal Instabilities and Edge Flames in Counterflow Slot-Jets
August 25, 1998	Paul Clavin	Cellular Overdriven Detonations
August 27, 1998	Christophe Clanet	On the Glug-Glug of the Bottle and Other Nonlinear Oscillators
December 2, 1998	Gregory T. Linteris	Fire in Space
January 8, 1999	Fernando Fachini	Theory of Microgravity Droplet Combustion
January 29, 1999	Fabian Mauss	A Detailed Kinetic Study of Soot Formation in Flames
February 5, 1999	Bruce Chehroudi	Initial Growth Rate and Visual Characteristics of a Round Cryogenic Jet into a Sub-to Supercritical Ambient Condition

DATE	SPEAKER	TITLE
February 22, 1999	George Kosaly	Discussion of the Quasisteady Approach to the Modeling of Diffusion Flames
March 5, 1999	Paul Linden	Recent Developments in the Fluid Mechanics of Ventilation
March 10, 1999	A.K. Oppenheim	Thermostatics and Thermokinetics of Closed Combustion Systems
March 19, 1999	Tadao Takeno	Structure of Methane-Air Coflow Diffusion Flame
June 3, 1999	Carlos Fernandez-Pello	Issues and Opportunties in MEMS
June 24, 1999	Lourdes Maurice	Future Fuels
July 19, 1999	R. W. Bilger	Recent Progress in CMC Closure for Turbulent Jet Diffusion Flames
August 9, 1999	Antonio Sanchez	The Reduced Kinetic Description of Lean Premixed Combustion
August 11, 1999	Ishwar K. Puri	Investigations of Partially Premixed (Double and Triple) Flames
August 12, 1999	Paul Ronney	Diffusive-Thermal Instability of Counterflow Flames at Low Lewis Number
August 16, 1999	Amable Liñán	Premixed Flames under Strain with an Overall Reaction of Large Activation Energy
August 18, 1999	Michel Champion	Turbulent Transport in Premixed Flames
August 20, 1999	K .N.C. Bray	Prediction of 'Rumble' Oscillations in a Gas Turbine Combustor
August 23, 1999	Tetsuo Hiraiwa	Experimental Investigation of Two-Stage Ethanol-Air Flames
August 25, 1999	Kurt Lund	Enhanced Heat Transfer at Micro-Fiber Surfaces
November 4, 1999	Kozo Saito	Flame Spread over Liquids – Recent Experimental Findings
February 8, 2000	Forman A. Williams	CECR Research Related to Pulse Detonation Chemistry
February 8, 2000	Juan Lasheras	CECR Research Related to Pulse Detonation Engines
March 21, 2000	A.K. Oppeneheim	Progress in Dynamics of Closed Combustion Systems
March 28, 2000	David Kassoy	A Unified Theory for Combustion-Driven Flow Dynamics in a Model of a Solid Rocket Motor Chamber
March 31, 2000	Norbert Peters	Stabilization of Lifted Turbulent Jet Diffusion Flames
April 17, 2000	Carlos Fernandez-Pello	Microgravity Ignition Delay of Solid Fuels in Low Velocity Flows

DATE	SPEAKER	TITLE
April 21, 2000	Howard Chang	The Three Gorges Project in China
May 5, 2000	Sandip Ghosal	Analysis of the Structure and Propagation of Triple Flames
May 19, 2000	C.K. Law	Accomplishments and Challenges in Combustion Science
August 21, 2000	Paul Ronney	Combustion in Microscale Heat-Recirculating Burners
August 23, 2000	K.N.C. Bray	Use of DNS Data to Test a Flamelet Model for Pressure Fluctuation Covariances in Premixed Turbulent Combustion
August 25, 2000	Paul Clavin	Galloping Detonations Close to the C-J Regime
August 28, 2000	Forman A. Williams	Chemical Effects in Counterflow Hydrocarbon Flame Structures
April 18, 2001	Robert Bitmead	A Skeptical Introduction to Combustion Instability Modeling
May 18, 2001	Al Sweedler	Energy Issues in the US-Mexican Binational Region: Focus on California – Baja California
August 13, 2001	K.N.C. Bray	Vorticity in Unsteady Premixed Flames
August 14, 2001	Emil Hopfinger	Liquid Jet Breakup and Atomization by a High Velocity Gas Stream
August 16, 2001	Paul Clavin	Diamond Patterns in Cellular Fronts of Overdriven Detonations
August 20, 2001	Amable Liñán	Laminar Mixing in Diluted and Undiluted Fuel Jets Upstream from Lifted Diffusion Flames
August 24, 2001	Marcos Coello	The Interaction of Vortices with Counterflow Reacting Layers
August 27, 2001	Paul Ronney	Premixed Flame Ignition by Corona Discharges
August 8, 2002	K.N.C. Bray	Combustion Oscillation in Burners with Fuel Spray Atomizers
August 13, 2002	Paul Clavin	Diamond Patterns of Gaseous Detonations (A Weakly Nonlinear Analysis of Overdriven Waves)
August 15, 2002	Amable Liñán	The Flow Field Induced in a Gas by Localized Energy Sources
August 20, 2002	K. Seshadri	Extinction of Partially Premixed Flames

DATE	SPEAKER	TITLE
August 22, 2002	Sutanu Sarkar	Turbulent Reacting Shear Flows: DNS and LES
August 27, 2002	Forman A. Williams	Flame Edges
August 29, 2002	Marcos Vera	Effects of Heat Release in Diffusion-Flame Stabilization via Triple Flames
October 8, 2002	Alex Bonne	Ion Sources for Ion Implantation of Semiconductors
October 15, 2002	Matthew Baldwin	Behavior of Liquid Lithium Surfaces in Contact with Plasma
October 22, 2002	Jill Dahlburg	The ISOFS Initiative: Integrated Simulation and Optimization of Fusion System
October 29, 2002	Bill Heidbrink	An Overview of Fast Particle Physics in MFE Devices
November 5, 2002	George Tynan	Plasma-Neutral Interactions in Plasma Processing
November 12, 2002	Marlene Rosenberg	Dusty Plasmas in Terrestrial and Space Applications
November 19, 2002	Steve Allen	Progress in Sustaining a Star on Earth: Improving the Magnetic Bottle (Tokamak) with Plasma Surgery and Floating the Plasma Away from the Walls
November 26, 2002	S. S. Harilal	Internal Structure and Expansion Dynamics of Laser Ablation Plumes
December 3, 2002	G. E. Lucas	Integrated Experiment Modeling Program for Fusion Reactor Materials
February 3, 2003	Alessandro Gomez	Gaseous and Spray Laminar Diffusion Flames Interacting with Toroidal Vortices: Inching Towards Turbulent Combustion
May 5, 2003	Vedha Nayagam	Pattern Formation in Diffusion Flames Embedded in Von Karman Swirling Flows
May 12, 2003	Indrek Wichman	Fluid Dynamics in Combusting Flows: Some New Results for Old Problems
May 19, 2003	Paul A. Libby	The Influence of a Thermally Active Wall on Premixed Turbulent Combustion
June 2, 2003	Ann Karagozian	Experiments and Simulations of Controlled Transverse Jets
August 8, 2003	David Meyerhofer	Progress in Direct-Drive Inertial-Confinement Fusion

DATE	SPEAKER	TITLE
September 8, 2003	Giacomo Aiello	SiCf/SiC Composites as Structural Material for the TAURO Fusion Blanket
September 19, 2003	Zhiyu Zhang	Ultrafast Laser Ablation and Plasma Diagnostics
October 21, 2003	Elio D'Agata	Mechanical and Thermal Aspects of the ITER Divertor
October 23, 2003	Zoran Dragojlovic	Chamber Gasdynamic Responses in IFE Chambers
October 30, 2003	Bindhu Harilal	Energy Absorption and Propagation Characteristics of Laser Induced Sparks
October 31, 2003	Mark Tillack	Laser Ablation Plume Dynamics and Particulate Generation
November 6, 2003	S. S. Harilal	Laser Produced Plasma Sources for EUV Lithography
November 13, 2003	Beau O'Shay	Magnetic Diversion of Laser Ablation Plumes
November 19, 2003	Susana Reyes	Latest Developments on IFE Materials Response and Safety Studies at LLNL
November 20, 2003	Patrick Calderoni,	Experimental and Numerical Study of Transient Condensation of Lithium and Beryllium Fluoride Excited Vapors for IFE Systems
December 5, 2003	Andy Bayramian	Enabling Technologies of the Mercury Laser: A Testbed for a Diode-Pumped Solid-State Laser Inertial Fusion Energy Driver
December 11, 2003	Xueren Wang	Compact Stellarator Power Plant Maintenance

12. PUBLICATIONS OF CER PERSONNEL

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i. Combustion

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b. PhD Theses

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J.C. Hewson, **"Pollutant Emissions from Nonpremixed Hydrocarbon Flames"**, 1997.

Ø. Hovde, **"Experimental and Theoretical Studies of Nox Formation in Lean Premixed Flames in Stagnation Flow,"** 1997.

B.L. Zhang, **"Microgravity Studies of Methanol Droplet Combustion"**, 1997.

M.D. King, **"Gravitationally Affected Combustion,"**(Joint Doctoral Program) 1999.

Reinhard Seiser, **"Nonpremixed Combustion of Liquid Hydrocarbon Fuels,"** 2000.

Alexander Telengator, **"Analyses of Combustion Processes in Porous Energetic Materials"**, 2000.

M. M.Y. Waly, **"Gaseous Hydrocarbon-Air Combustion in Two-Stage Flames"**, 2000.

Leonard Truett, **"Experimental Studies of Inhibited Counterflow Flames,"** 2001.

Balachandar Varatharajan, **"Study of Ignition and Detonation of Hydrocarbon-Air Mixtures with Detailed and Reduced Chemical Mechanisms,"** 2001.

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Chris Varga, **"Atomization of a Small-diameter Liquid jet by a High-speed Gas Stream**, 2002.

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Dustin Blair, **"Mechanisms of Particulate Formation in Laser Plasma,"** 2003.

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E. Sundt, **"Injector and Ignition Studies for APU-applications"**, 1999.

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M. Jenson and S. Humer, **"Nonpremixed Extinction of Ethane"**, 2000.

K.H. Lien, **"An Experimental Investigation of Diluted Hydrogen-Air Counterflow Diffusion Flames"**, 2000.

J.P. Pettersen, **"Experimental Investigation of Two-Stage Premixed Hydrogen Flames"**, 2000.

F.H. Redell, **"Experimental Investigation of the Structure of a Partially Premixed Planar Ethanol Flame"**, MS Thesis, 2000.

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Edgar Piskernik, **"Experimental and Numerical Studies of Combustion of Methanol and Ethanol,"** MS Thesis, 2001.

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13. FINANCIAL SUPPORT FOR CER

CER Grants

Funding Source	Title	PI	Current Funding (2003)
GA	Divertor Materials Evaluation Systems (DiMES) Coordinator	Moyer/Rudakov	49,847
DOE	Edge Physics and Disruption Experiments on the DIII-D	Luckhardt, Moyer, Boedo	560,000
Oakridge Nat'l Labs	National Compact Stellarator Experiment	Luckhardt	30,000
DOE	PISCES Program: Advanced Fusion Materials and Plasma Science of Boundary Interactions	Conn, Luckhardt, Doerner	1,850,001
Univ of Texas, Austin	Magnetized Plasma Turbulence and Coupling to Bulk Flows	Luckhardt	50,000
Archimedes	Unrestricted Gift	Tynan	70,000
GA	Analysis Tools and Techniques for Beam Emission Spectroscopy Studies on DIII-D	Tynan	61,001
DOE	Edge Physics Studies on the NSTX Spherical Tokamaks	Boedo, Moyer	160,000
DOE	New Diagnostic for Boundary Plasma	Boedo	50,000
DOE	Edge, SOL, and Divertor Plasma Turbulence and Macroscopic Transport	Krasheninnikov	200,249
LLNL	Electron kinetic models for IFE studies	Krasheninnikov	38,012
GA	Transport Modeling and Theoretical Support	Krasheninnikov	40,289
DOE	Modeling of far SOL Plasma Transport in NSTX	Krasheninnikov	62,974

Funding Source	Title	PI	Current Funding (2003)
JPL	Ion Thruster Technology Investigation	Doerner	100,000
Von Liebig	Extending Ion Thruster Enging Lifetime	Doerner	49,161
Alta Sr1	Lifetime Extension of Ion Thruster Grids	Doerner	40,000
ORNL/Bechtel/Lockheed	Virtual Laboratory for Technology	Baker	730,000
DOE	Advanced Design Program	Najmabadi, Tillack	908,999
DOE	Analysis of High-Harmonic Fast Wave Current Drive and Heating in NSTX Discharges	Mau, Najmabadi	50,000
DOE	IFE Chamber Dynamics and Laser Propogation Simulation Tests	Tillack, Najmabadi	190,045
GA	Target/Chamber Interface RandD	Raffray, Tillack	170,000
Fusion Subtotal			**5,460,579**
AFOSR	Combustion Processes and Instabilities in Liquid-Propellant Rocket Engines	Williams	90,094
NASA	Stretched Diffusion Flames in von Karman Swirling Flows	Williams	10,065
NSF	Theory of Combustion by Analytical Methods for Real Chemistry	Williams	240,000
NSF	Burning Velocites of Flamelets in Turbulent Premixed Flames	Williams	12,050
NASA	High Pressure Combustion of Binary Fuel Sprays	Williams	31,668
NASA	Scientific Support for a Proposed Space Shuttle Droplet Burning Experiment	Williams	85,000
NASA	Dynamics of Droplet Extinction in Slow Convective Flows	Williams	8,590

Funding Source	Title	PI	Current Funding (2003)
UC Presidents Office	Presidential Chair in Energy and Combustion Research	Williams	149,184
Vice Chancellor	Cash Contributions	Williams	45,150
Chancellor	Cash Contributions	Williams	24,080
Civilian Research Development Foundation	Ignition and Combustion of a Solid Particle Suspension in Gas Containing and Oxidant and a Combustible Component	Williams	8,601
UC Foundation	Catalytic Combustion	Williams	22,000
Sundstrand Power Systems	Gift Funds	Williams	6,254
Various Doners	Gift Funds	Williams	, 500
ARO	Chemical-Kinetic Characterization of Autoignition and Combustion of Diesel and JP-8	Seshadri	40,000
NSF	Chemical-Kinetic Characterization of Ignition of Fuels	Seshadri	225,000
Energy Science Lab	Gift Funds	Lund	10,000
Combustion Subtotal			**1,008,236**
		FUSION	**5,460,579**
		COMBUSTION	**1,008,236**
		TOTAL CER FUNDING	**6,468,815**

14. EXPENDITURE BREAKDOWN

INCOME	7/1/96- 6/30/97	7/1/97-6/30/98	7/1/98-6/30/99	7/1/99- 6/30/00	7/1/00-6/30/01	7/1/01-6/30/02
FEDERAL GRANTS AND CONTRACTS	5,170,896	5,797,766	5,921,971	7,947,939	9,604,017	10,474,913
FOUNDATIONS AND PRIVATE GIFTS	53,035	59,464	60,738	81,517	98,503	107,435
UCSD/UC DERIVED	79,552	89,196	91,107	122,276	147,754	161,153
TOTAL	**5,303,483**	**5,946,426**	**6,073,816**	**8,151,732**	**9,850,274**	**10,743,501**

SUPPLIES	7/1/96- 6/30/97	7/1/97-6/30/98	7/1/98-6/30/99	7/1/99- 6/30/00	7/1/00-6/30/01	7/1/01-6/30/02
FEDERAL GRANTS AND CONTRACTS	519,412	485,037	327,676	961,047	1,023,679	1099534.8
FOUNDATIONS AND PRIVATE GIFTS	10,935	10,211	6,898	20,233	21,551	11277.28
UCSD/UC DERIVED	16,402	15,317	10,348	30,349	32,327	16915.92
TOTAL	**546,749**	**510,565**	**344,922**	**1,011,628**	**1,077,557**	**1,127,728**

EQUIPMENT	7/1/96- 6/30/97	7/1/97-6/30/98	7/1/98-6/30/99	7/1/99- 6/30/00	7/1/00-6/30/01	7/1/01-6/30/02
FEDERAL GRANTS AND CONTRACTS	489,012	870,315	687,544	709,920	847,891	1228979.7
FOUNDATIONS AND PRIVATE GIFTS	10,295	18,322	14,475	14,946	17,850	12604.92
UCSD/UC DERIVED	15,442	27,484	21,712	22,419	26,776	18907.38
TOTAL	**514,749**	**916,121**	**723,730**	**747,284**	**892,517**	**1,260,492**

PERSONNEL

	7/1/96- 6/30/97	7/1/97-6/30/98	7/1/98-6/30/99	7/1/99- 6/30/00	7/1/00-6/30/01	7/1/01-6/30/02
GRAD STUDENTS	295,852	170,075	163,594	190,513	231,622	89,926
ADMINISTATIVE	147,926	85,037	81,797	95,257	115,811	44,963
TECHNICAL	554,723	318,891	306,738	357,212	434,292	168,612
ACADEMIC	2,699,652	1,551,940	1,492,796	1,738,434	2,113,557	820,578

15. FACILITIES AND SPACE OF CER

Professors who are members of the CER have their own offices in Engineering Building Unit II (EBU II). Office space is also provided for graduate students, research scientists and staff and visitors in EBU II. Laboratory space (some of which houses desks and office space for laboratory engineers, technicians and experimental research students) for the CER are located in the basement area of EBU II. The space for all offices is allocated per University guidelines: faculty and senior research staff are given their own office, junior research scientists and engineers and postdoctoral students are housed two per office, and graduate students are housed three per office. A general-use conference room and library is also part of the CER's space allotment and is located on the fourth floor of EBU II. Although officially designated CER space is insufficient, CER cooperates closely with MAE (which is officially assigned the majority of the space in EBU II) to achieve an equitable distribution of space. The assigned Center for Energy Research occupies 48 spaces and 16,673 square feet of assignable space. The following tables summarize the usuage of space at CER space (which does not include MAE- assigned space occupied by CER personnel).

TABLE I. 2004 INVENTORY OF CER ASSIGNED SPACE

SPACE	ROOM USE	DEPARTMENT	SQUARE FEET
B12	Research Laboratory/Studio	Center for Energy Research	1,700
B13	Research Lab/Studio Service	Center for Energy Research	100
B14	Research Laboratory/Studio	Center for Energy Research	1,950
B15	Research Laboratory/Studio	Center for Energy Research	530
B16	Research Laboratory/Studio	Center for Energy Research	950
B17	Research Laboratory/Studio	Center for Energy Research	1,130
B26	Research Laboratory/Studio	Center for Energy Research	3,550
B29	Research Laboratory/Studio	Center for Energy Research	820
358	Research Office	Center for Energy Research	132

SPACE	ROOM USE	DEPARTMENT	SQUARE FEET
359	Research Office	Center for Energy Research	132
360	Research Office	Center for Energy Research	132
361	Research Office	Center for Energy Research	132
362	Research Office	Center for Energy Research	132
363	Research Office	Center for Energy Research	132
364	Research Office	Center for Energy Research	132
365	Research Office	Center for Energy Research	132
366	Research Office	Center for Energy Research	132
455	Research Office	Center for Energy Research	132
456	Research Office	Center for Energy Research	132
457A	Research Office	Center for Energy Research	132
457B	Research Office	Center for Energy Research	132
457C	Research Office	Center for Energy Research	132
458A	Research Office	Center for Energy Research	132
458B	Research Office	Center for Energy Research	132
459A	Administrative Office	Center for Energy Research	132
459B	Administrative Office	Center for Energy Research	132
460A	Administrative Office	Center for Energy Research	132
460B	Administrative Office	Center for Energy Research	132
460C	Administrative Office	Center for Energy Research	132
464	Research Office	Center for Energy Research	132
554	Administrative Office	Center for Energy Research	132
555	Academic Office	Center for Energy Research	132
556	Research Office	Center for Energy Research	132

SPACE	ROOM USE	DEPARTMENT	SQUARE FEET
557	Academic Office	Center for Energy Research	132
558	Academic Office	Center for Energy Research	132
559	Academic Office	Center for Energy Research	132
560	Academic Office	Center for Energy Research	132
561	Research Office	Center for Energy Research	132
562	Research Office	Center for Energy Research	132
563	Research Office	Center for Energy Research	132
564	Research Office	Center for Energy Research	132
565	Administrative Office	Center for Energy Research	131
565A	Administrative Office	Center for Energy Research	132

16. FUTURE DIRECTIONS AND NEEDS

Over the next five years, CER is envisioned as having three principal themes:

- plasma and fusion energy science,
- fundamental and applied combustion science,
- alternative technologies and energy assessments.

The first two themes are well established and have an excellent future with many opportunities for new and/or expanded research tasks. The third theme is in a formative phase and needs to grow over the next five years.

a. Plasma and Fusion Energy Science

Nuclear fusion holds the promise of a long-term energy solution with potentially less environmental impact than other long-term energy sources. Turning this promise into reality, however, is an extremely challenging task, which requires continual progress in experimental, theoretical and computational research, since the fusion process proceeds only at very high temperatures that occur only in the plasma state. There are two main approaches to achieving nuclear fusion. One is to use magnetic fields to confine the plasma state (magnetic confinement) and the other is to use high-power lasers to repetitively produce the plasma state (inertial fusion). Future CER thrusts will address both of these approaches.

Researchers in CER have recently established a laboratory for studying laser-materials interactions relevant to inertial fusion. Future plans are to employ this facility for experimental investigations of materials responses relevant not only to inertial fusion but also to magnetic confinement. Associated theoretical research is planned for increasing understanding of laser-materials interactions. This understanding is to be applied to advance prospects for achieving controlled nuclear fusion.

The PISCES facility will be employed for studying confinement and wall problems associated with magnetic plasma confinement. Objectives include how to confine such plasmas more efficiently and to understand better how heat and particles escape from such plasmas. Associated theoretical work will address instabilities and turbulent structures in these plasmas. Inputs to future designs, such as ITER, are planned.

b. Fundamental and Applied Combustion Science

Improvements in energy use and combustion are becoming increasingly important as the finite supply of fossil fuels decreases. CER is concerned with research advancing abilities to utilize fossil fuels properly. A central objective is to determine how to burn fuels more cleanly, efficiently and safely. Ramifications extend to considerations of fire and explosion safety, air pollution, waste incineration, greenhouse-gas reduction, ozone depletion and vehicle propulsion on the earth's surface, in the air and in space. A myriad of evolving societal problems can benefit from the knowledge being developed in combustion research.

Examples of ongoing CER research in combustion-related areas are projects in mitigation of combustion-generated air pollution, propellant combustion and combustion instability, determination of how combustion is affected by the gravity-free conditions existing in space vehicles, destruction of toxic and non-toxic waste materials, and finding replacements for halogen-containing fire suppressants to reduce ozone depletion. On the applications side, CER is strongly interested in real-world problems such as the efficient use and production of energy, the propulsion of airborne and exoatmospheric vehicles, improved cleanliness and performance of mobile power plants, aspects of materials processing, such as self-propagating high-temperature synthesis, and practical uses of catalysis in combustion.

Future plans in the short term are to increase fundamental knowledge of combustion processes in a number of ways. These specifically include: clarifying mechanisms of hydrogen autoignition and combustion, relevant to both hypersonic propulsion through supersonic combustion (needed for single-stage-to-orbit vehicles) and improved nuclear fission-reactor safety; ascertaining combustion and explosion mechanisms of porous solid materials representative of aging and degraded propellants, of concern in the disposal of outdated munitions; elucidation of mechanisms of ethanol ignition and combustion, important for studies of alternative automotive fuels; identification and characterization of combustion mechanisms of surrogate fuels that simulate existing practical fuels but are more amenable to unambiguous, detailed scientific study and offer promise for development of a single universal fuel for defense applications; advancement of diagnostic methods for combustion investigations, such as laser-induced fluorescence (LIF), laser-induced breakdown spectroscopy (LIBS) and laser-diode techniques for detection of low levels of nitric-oxide pollutants; helping to clarify the mechanisms by which fire resulted in the collapse of the Twin Towers, of importance to the future of high-rise fire safety; and identifying how free and fiber-supported hydrocarbon droplets burn in variable convective flows in microgravity, through experiments to be performed in the International Space Station.

Advances in these areas will make use of experiments in the CER combustion laboratories, computations performed with CER computer facilities and theoretical analyses by CER graduate students, post-doctoral researchers and faculty. In the longer term, CER envisions new thrust areas for combustion research. These include: homogeneous-charge compression ignition (HCCI), an engine concept that, in theory, may rival hybrids and fuel cells for clean and efficient automotive power, provided that associated control problems can be solved; supersonic-combustion ramjet propulsion (SCRAM jet), a primarily hydrogen-based combustion concept that is most promising for aerospace propulsion; and alternative fuels for reduction of pollution in stationary and mobile power plants, bringing CER knowledge to bear on problems of emissions of oxides of nitrogen, soot, toxics and greenhouse gases.

c. Alternative Energy Technologies and Energy Assessments

The broad area in which future plans call for strengthening the CER presence is the area of Alternative Energy Technologies and Energy Assessments. The CER activities in this area are largely championed by Professor S.S. Penner, the founder and first Director of the Center. The wide-ranging impact of energy developments calls for a highly cross-disciplinary approach to addressing the many issues that fall in this broad area.

Future CER plans are that, with broadened funding, new intensive thrusts will be mounted on topics selected from the following areas:

- Energy Production in Fuel-Cell and Hybrid Systems
- Development of Renewable Energy Technologies
- Economics of Energy Needs and Resources
- Fossil Fuel Recovery and Use
- Reduction of Air Pollution from Fuels and Combustion
- Assessments of Energy Conservation Initiatives

- Environmental Effects of Trace Species
- Toxic Waste Disposal
- Mitigation of Greenhouse-Gas Effects
- Energy and Environmental Implications of the Hydrogen Economy

Strengthening the CER presence in any of these areas would increase the interdisciplinary character of the center and broaden its impact on policy issues. Many of these topics are closely associated with environmental research issues and thus offer excellent opportunities for collaborative research between scientists in CER and in environmental research programs at UCSD, for example those in MAE, SIO and Chemistry.

d. Financial and Space Resources Needed

Currently the CER has an annual budget of $6.47M which comes from several funding agencies; e.g., NSF, DOE, NASA, ORNL, LLNL, ONR, UC SMART, UCOP, UCEI and General Atomics Co. The CER has 12 faculty, 18 research and post-graduate research staff, 22 affiliated graduate students and 24 laboratory and administrative staff for a total participation of nearly 80 people. The Center staff and laboratories currently occupy about 13,000s.f. of space, mainly in Engineering Building Unit II.

The four and seven-year projections of Center funding, faculty, staff, students and space are summarized in Table II. The indicated growth in research expenditures is considered very achievable given anticipated growth in the fusion and combustion areas along with a broadening of Center activities in the direction of alternative energy technologies (e.g., fuel cells) and/or energy assessment studies. Growth in research and support staff will track this projected growth in funding.

Table II. CER Resource Summary

	2003 (Current)	2007 (Projection)	2010 (Projection)
Research Funding	$6.47M	$10.0M	$12.0M
Faculty	12.0	2.0	5.0
Affiliated Faculty	14.0	13.0	22.0
Graduate Students*	24.0	35.0	50.0
Research Staff	17.0	30.0	35.0
Engineering and Technical Staff	17.0	20.0	25.0
Support Staff	6.0	7.0	8.0
Space	13,000 s.f.	19,000 s.f.	23,000 s.f.

***It is assumed CER affiliated faculty will also have graduate students not associated with the CER.**

The present space occupied by the CER (space previously designated for the CECR, and space provided by the MAE Department) is fully occupied with no room for more staff and laboratories. As the CER research funding grows, commensurate growth in space will be needed. This will require about an additional 10,000 square feet of space over the next ten years.

It is proposed that faculty having membership in the CER be increased by two over the next three to four years and by a total of seven over the next seven years. It is anticipated that the FTE's will not be allocated to the CER but will be allocated to a home academic department for each faculty member. The same approach will continue to be followed for graduate students. Thus, academic departments will be responsible for providing the space for faculty and graduate students.

Presently, the majority of the administrative staff (six people) are paid out of research grants, which is not appropriate. Most, if not all, of the administrative staff should be paid out of Center funds received from the Office of the Vice Chancellor for Research. This will need to be increased, probably in a step-wise fashion, over the next three years.

It is proposed to work with appropriate departments to recruit the desired new faculty members in some of the following areas:

- One senior faculty member to lead an area of fuel cells, renewable energy or energy assessment and policy studies.
- A junior faculty member as the interface between energy and environmental research.
- A junior faculty member in the area of plasma-assisted nano-scale manufacturing.
- A junior faculty member in computational plasma physics or laser-plasma interactions.
- A junior faculty member in combustion chemistry.
- A junior faculty member in computational combustion with detailed chemistry or in computational modeling of engine combustion.

APPENDIX

The following is a sample issue of the CER Newsletter.

UCSD

Volume 2, No. 2
June 2002

University of California, San Diego
Center for Energy Research

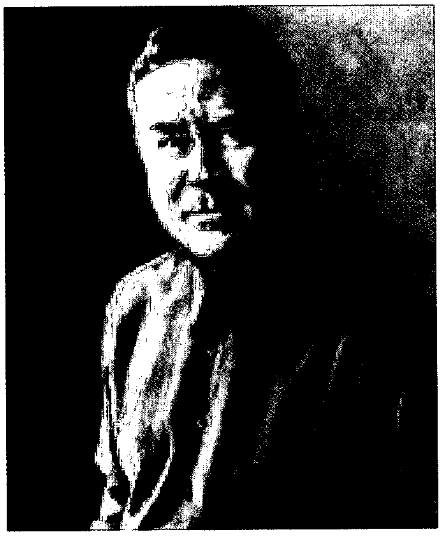
Center for Energy Research Newsletter

In This Issue

UCSD

Volume 2, No. 2
June 2002

Energy Transitions: A History Lesson



Richard Rhodes
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By Richard Rhodes

The following article[*] is the text of the keynote address delivered by Richard Rhodes on April 8, 2002 to the members of the Sixth International Symposium on Fusion Nuclear Technology in San Diego, CA.

Energy sustains life. Energy drives and supports the fundamental human project, which is the alleviation of suffering through the progressive materialization of the world. The inanimate world is cold and silent and indifferent and inhumane until human imagination transforms it. Imagination transforms the inanimate by shaping it into materials, machines, systems and connections invested with compassion, as if it were human and wished us well: the chair by its invented structure supporting us against gravity, hybrid corn and rice feeding us, vaccines boosting our immune systems, steel and clay and concrete sheltering us, electricity wound of wires or radiated through the air connecting us together and lighting our way.[i]

Gross national product depends on energy supply, and GNP per capita correlates directly with life expectancy. The correlation between per-capita GNP and life expectancy has been called "the Economic Law of Life." Even more specifically, electricity use per capita correlates directly with a measure of the quality of human life. Both these correlations reveal an indirect form of human violence: structural violence, violence built into the structure of societies according to the way power and wealth are distributed. The average ten years' shorter life expectancy of African-Americans in the United States, for example, quantifies the structural violence of racial prejudice, reduced today but long sustained. Structural violence historically has been addressed two ways: through war and civil conflict, or through economic development. If the structural violence still abroad in the world is to be reduced with a minimum of war and civil conflict—if the suffering implicit in these correlations is to be alleviated—then the world will need more energy, not less. Until life expectancy for everyone in the world advances to at least 70 years, until everyone in the world has access to at least 4,000 kilowatt-hours of electricity, efforts to limit energy supply, however idealistically intended, will be acts of violence.

Energy transitions take time.[ii] "Hardly any innovation diffuses into a vacuum," writes Arnulf Grübler. "Along its growth trajectory," he continues, "an innovation interacts with existing techniques, depends on the development of a mediating framework for its effective absorption

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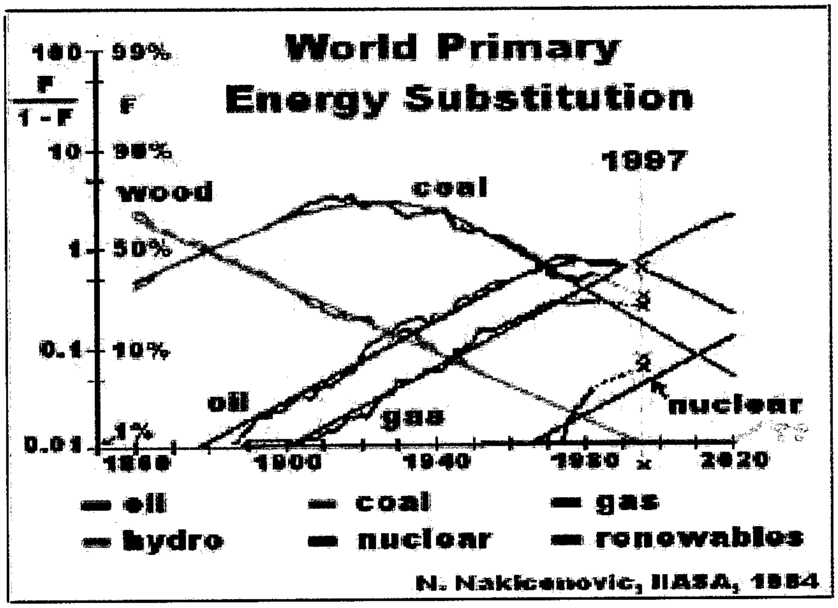
[*] A list of footnote sources and references can be found on the last two pages of this newsletter.

into the sociotechnical system, and changes its technological, economic, and social characteristics....Decades are required for the diffusion of significant innovations, and even longer time spans are needed to develop infrastructures of pervasive sociotechnical systems."[iii] The diffusion process is a process of learning, and humans learn slowly. The International Institute for Applied Systems Analysis studied the historical evolution of the world's primary energy mix across the years from 1860 to 1997 and found "a regular pattern in the substitution of one source for another over decades."[iv] Here primary energy consumption is graphed logistically as a fraction of world market share in tons of coal equivalent. Irregular lines are historical data; smooth lines are logistic projections. "This competition has been stable over the past 150 years," writes Cesare Marchetti, "with three energy crises and related price increases and wars and depressions leaving no dents in the mechanism."[v] Note that renewables have not yet even penetrated to the one-percent threshold. The dream of the Greens that renewables will somehow substitute for nuclear power in the next few decades defies historical reality.

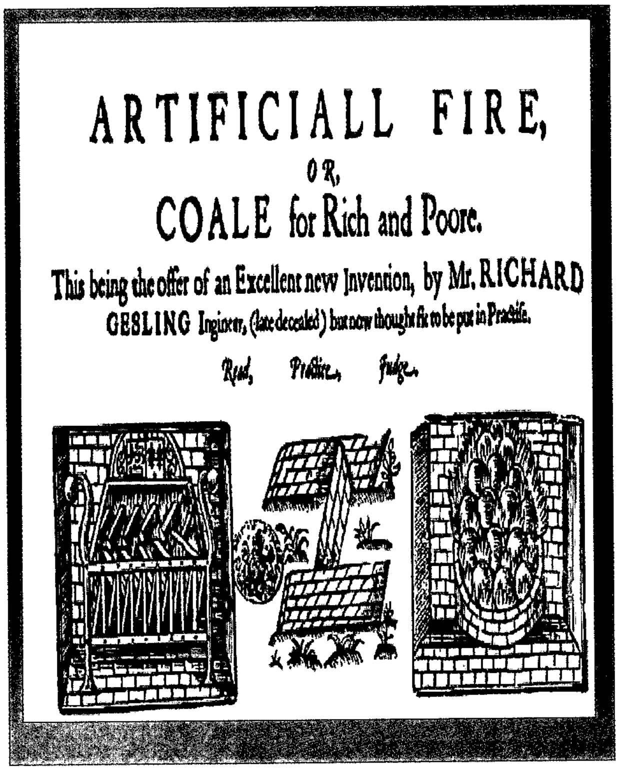


N. Nakicenovic, IIASA, 1984

The historic substitution of coal for wood was fundamental to the Industrial Revolution. Coal had been known and used for three thousand years, but only marginally. Its social characteristics were wrong for a society organized around burning wood: compared to wood, it was dirty; it stank; it required different skills and technologies to collect and distribute; and its smoke was more toxic. In Tudor England, where woodsmoke was believed to harden the house timbers and disinfect the air, chimneys were uncommon; the smoke from fires was simply allowed to drift out the windows.[vi] But sixteenth-century London suffered from a problem familiar to urban conurbations in developing countries today: as the city grew, a farther and farther area around it became deforested, and as transportation distances increased, wood became more expensive. The poor had to switch to coal; the rich resisted. "Even in late Elizabethan times," writes a historian, "...it was evident that the nobility still objected strongly to the use of the fuel. Well-bred ladies would not even enter rooms where coal had been burnt, let alone eat meat that had been roasted over a...coal fire, and the Renaissance Englishman was not keen to accept beer tainted with the odor of coal smoke."[vii]

Brewing was one London industry that turned to coal as wood and charcoal became scarce; so did dyers, limeburners and salt- and soap-boilers. The nobility began to accept the transition when Queen Elizabeth died in 1603 and the throne passed to James I, who had been James VI of Scotland. Scottish nobles had faced wood shortages earlier than the English and had access to less sulphurous coal, "so the new king used the fuel in his household when he moved to London."[viii] Coal became fashionable, and none too soon. By 1700, coal production in England and Wales had reached three million tons per year—half a ton per capita.[ix] By 1800, production had tripled to nine million tons per year.[x]

There were two fundamental technological challenges to increasing coal production. One was that deepening coal mines penetrated the water table and flooded the mines: the water needed to be pumped away. [8: NEWCOMEN ENGINE] Steam engines were developed first of all for pumping coal mines. "...Three quarters of the patents issued in England between 1561 and 1668 were connected with the coal industry...and...a seventh were concerned with the drainage problem."[xi] And since steam engines burned coal, the new energy source was bootstrapping itself.



ARTIFICIALL FIRE,
OR,
COALE for Rich and Poore.
This being the offer of an Excellent new Invention, by Mr. RICHARD
GESLING Inginer, (late deceaſed) but now thought fit to be put in Practiſe.
Read, Practiſe, Judge.

The other fundamental challenge was transportation. Wood, which grew dispersed across the landscape, could be transported efficiently in small batches in carts and on river boats. Coal was not areal, like wood, but punctiform—that is, it came out of a hole in the ground—and efficiency required its transportation in bulk. At first it was delivered by sea from mines near ports. There were 400 smaller colliers—boats carrying coal—working between Newcastle and London in 1600; by 1700 that number had increased to 1,400, and the boats were larger. By 1700 "about half of the total British merchant fleet by tonnage was engaged in the coal trade."[xii] But as use grew and mines were opened inland, coal drove the development of canals.

Then the technologies developing to meet the challenges of coal production combined. The first railways, horse-drawn, had connected pitheads with coal wharves to move coal onto colliers for transport by sea. The steam engine, mounted on wheels that ran on rails, offered faster and more powerful transportation. "Railways were peculiarly a mining development (even down to the track gauge)," an English historian explains, "and were created to overcome the problems posed by large-scale punctiform mineral production, initially as feeders to waterways, but later as an independent network. Like canals, they also, of course, proved in time of great benefit to other forms of production and made easier the movement of the vegetable and animal raw materials. Moreover, they developed a great passenger traffic."[xiii]

Energy transitions transform societies. Let me quote two somewhat opposing views of the coal transformation, to demonstrate how complex such transformations are. Both the writers are economists. The first view:

> *The abundance and variety of [the Industrial Revolution's] innovations almost defy compilation, but they may be subsumed under three principles: the substitution of machines—rapid, regular, precise, tireless—for human skill and effort; the substitution of inanimate for animate sources of power, in particular the introduction of engines for converting heat into work, thereby opening to man a new and almost unlimited supply of energy; the use of new and far more abundant raw materials, in particular the substitution of mineral for vegetable or animal substances.*
>
> *These improvements constitute the Industrial Revolution. They yielded an unprecedented increase in man's productivity and, with it, a substantial rise in income per head. Moreover, this rapid growth was self-sustaining. Where previously, an amelioration of the conditions of existence...had always been followed by a rise in population that eventually consumed the gains achieved, now, for the first time in history, both the economy and knowledge were growing fast enough to generate a continuing flow of investment and technological innovation, a flow that lifted beyond visible limits the ceiling of Malthus's positive checks. The Industrial Revolution thereby opened a new age of promise. It also transformed the balance of political power, within nations, between nations, and between civilizations; revolutionized the social order; and as much changed man's way of thinking as his way of doing.*[xiv]

The second view:

> *This account has the merit of symmetry, but the notion of substitution is problematic, since in many cases there are no real equivalents to compare. The fireman raising steam in an engine cab, or the boilermaker flanging plates in a furnace, were engaged in wholly new occupations which had no real analogy in previous times....If one looks at technology from the point of view of labor rather than that of capital, it is a cruel caricature to represent machinery as dispensing with toil. High-pressure engines had their counterpart in high-pressure work, endless chain mechanisms in non-stop jobs. And quite apart from the demands which machinery itself imposed there was a huge army of labor engaged in*

> *supplying it with raw materials, from the slave laborers on the cotton plantations of the United States to the tinners and copper miners of Cornwall. The industrial revolution, so far from abridging human labor, created a whole new world of labor-intensive jobs: railway navvying is a prime example, but one could consider too the puddlers and shinglers in the rolling mills, turning pig-iron into bars, the alkali workers stirring vats of caustic soda, and a whole spectrum of occupations in what the Factory legislation of the 1890s was belatedly to recognize as "dangerous" trades. Working pace was transformed in old industries as well as new, with slow and cumbersome methods of production giving way, under the pressure of competition, to overwork and sweating.*[xv]

The second great energy transition originated in the United States, and like the transition to coal, it began with a preadaptation. Coal's preadaptation was its substitution for domestic woodburning, which then led to its application to steam power in mining, transportation and manufacturing. Oil was first used as a substitute for whale oil for illumination in the form of kerosene, another example of substituting mineral for animal or vegetable raw materials. [12: OIL DERRICKS] "Rock oil emits a dainty light," a pamphleteer wrote in 1860, a year after Uncle Billy Smith struck oil at Oil Creek in Titusville, Pennsylvania, "the brightest and yet the cheapest in the world; a light fit for Kings and Royalists and not unsuitable for Republicans and Democrats."[xvi] Kerosene remained the most important oil product for decades, with smaller markets developing for naphtha; gasoline, which was used as a solvent or gasified for illumination; fuel oil; lubricants; petroleum jelly and paraffin wax.

At the beginning of the twentieth century, coal still accounted for more than 93 percent of all mineral fuels consumed in the United States, and electric light was rapidly displacing the kerosene lantern in urban America, with 18 million light bulbs in use by 1902. Oil might have declined, because it was much more expensive per unit of energy than coal, but because it is a liquid it is also much cheaper to transport. Even as late as 1955, the cost per mile of transporting a ton of liquid fuel energy by tanker or pipeline was less than 15 percent of the cost of transporting an equal amount of coal energy by train. Large oil fields were discovered in Texas and California early in the century. Railroads in the West and Southwest almost immediately converted to oil burning, because local oil was cheaper than distant coal when transport was figured in. Total energy consumption in the U.S. more than doubled between 1900 and 1920, making room for oil to expand its market share without directly challenging the coal industry. Steamships offered another major market. The U.S. Navy converted to fuel oil before the First World War, a conversion which functioned as an endorsement for private shippers. And as with coal, a significant bootstrapping market was the oil industry itself, which used oil both to fuel its oil tankers and "to provide the intense heat needed for petroleum refining....An estimated [five to ten] percent of all oil produced in this period was burned in the refineries."[xvii]

The introduction of the automobile secured oil's market share. "Animal feed," writes Nebojsa Nakicenovic, "reached its highest market share in the 1880s, indicating that draft animals provided the major form of local transportation and locomotive power in agriculture....Horse carriages and wagons were the only form of local transportation in rural areas and basically the only freight transportation mode in cities. In addition, they moved goods and people to and from railroads and harbors."[xviii] Henry Ford's original intention was to develop a farm tractor, he recalled in his autobiography.

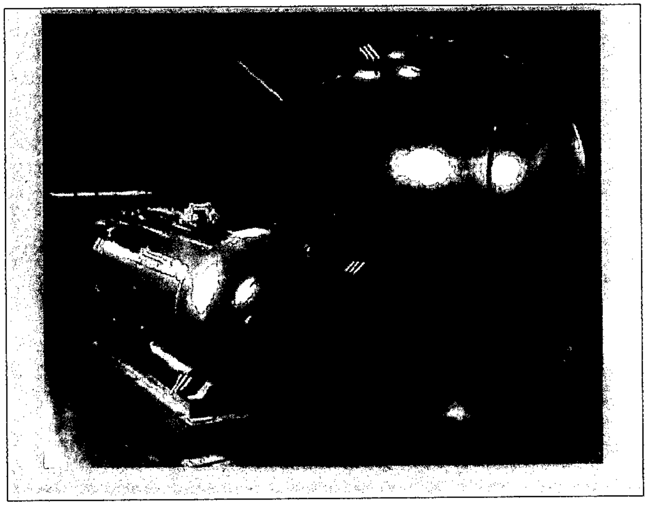
> *"It was not difficult for me to build a steam wagon or tractor," he wrote. "In the building of it came the idea that perhaps it might be made for road use....The obvious thing to do was to design and build a steam engine that would be light enough to run an ordinary wagon or to pull a plow. I thought it most important first to develop the tractor. To lift farm drudgery off flesh and blood and lay it on steel and motors has been my most constant ambition. It was circumstances that took me first into the actual manufacture of motor cars. I found eventually that people were more interested in something that would travel on the road than in something that would do the work on the farms."*[xix] *By manufacturing motor cars, Ford and his competitors relieved farm labor by reducing the demand for animal feed: in Great Britain, for example, the annual feed bill for town horses in the 1890s approached 100 percent of the annual value of all crops sold off British farms.*[xx]

In Nakecenovic's analysis, the automobile first substituted for and displaced the horse-drawn carriage, largely because it increased the radius of local transportation, allowing "entrepreneurs to expand their circles of customers and [offering] a more flexible mode of leisure and business transport."[xxi] Only after that process was completed, in the 1920s, "did it emerge as an important transportation mode in competition with the railroad for long-distance movement of people and goods."[xxii] Just at that time, natural gas began penetrating major industrial markets such as iron and steel, cement, textiles, food, paper and pulp which burned coal or had recently switched to fuel oil, *"freeing petroleum to meet the rising demand for gasoline."*[xxiii]

Preadaptations that prepared the way for the automobile included the availability of gasoline as a refinery byproduct and the surfacing of roads for horse-drawn carriages. Eight percent of all U.S. roads were already surfaced by 1905, when there were fewer than 80,000 automobiles in use but more than 3 million non-farm horses and mules.[xxiv] The diesel engine was originally conceived as a combustion engine for powdered coal, but the resulting ash ground and fouled its cylinders and pistons; diesel fuel, another refinery byproduct, made it practical.[xxv] By 1950, fuel wood comprised only 3.3 percent of aggregate U.S. energy consumption and natural gas 17 percent, but coal and oil closely matched each other with somewhat more than 36 percent each.[xxvi] Oil's market share peaked in 1968 at only 43 percent, much lower than coal's earlier peak of 70 percent. Natural gas had emerged to compete with oil only 20 years after oil's emergence. The gap had been much wider between coal and oil—about 150 years. Today both coal and oil are declining as fractions of total world energy, although oil demand is at a maximum. *"The oil industry still has most of its future in front of it,"* Marchetti predicts, with a mean loss of production across its decline of only

1.6 percent per year.[xxvii] But the longer future belongs to natural gas, which Marchetti expects to reach a maximum market share of 70 percent—"like coal"—around the year 2040.[xxviii] Natural gas had time to gain a large market share because its next competitor, nuclear power, emerged a long seven decades later. Seventy percent market share for gas will be a huge share of a huge market, and if you wonder where all the gas will come from, the answer seems to be that the search for hydrocarbons is controlled much more by geopolitics than by the probability of discovery.[xxix]

The preadaptation that prepared the emergence of nuclear power has continued to haunt it.[xxx] In the United States, the Soviet Union, Great Britain, France and China, nuclear reactors were developed first of all to breed plutonium for nuclear weapons. Power reactors were delayed in the United States in the years immediately after the Second World War because everyone involved in the new atomic energy enterprise believed that high-quality uranium ore was rare in the world, too rare to be diverted from weapons production. Early in the 1950s the U.S. Atomic Energy Commission even considered extracting uranium from coal ash, where burning had concentrated coal's natural complement of uranium ore. Well into that decade, almost the entire U.S. production of uranium and plutonium was dedicated to nuclear weapons. Finally the federal government offered bonuses to uranium prospectors for high-quality finds and the prospectors, reprising the California Gold Rush, unearthed the extensive uranium resources of the Colorado Plateau.



Another delay arose from concerns for secrecy. The Atomic Energy Act of 1946 made atomic energy an absolute monopoly of the federal government. All discoveries were to be considered "born" secret—treated as secret until formally declassified—and the penalty for divulging atomic secrets was life imprisonment or death. All uranium and plutonium became the property of the government, as beached whales once became the property of kings. No one could build or operate a nuclear reactor except under government contract, nor could one be privately owned. All these restrictions and mindsets had be revised before utilities could own or build nuclear power stations.

It is clear in hindsight that the careful evolutionary development of nuclear power in the United States, including the types of reactors developed and the nurturing of a solid political constituency, were casualties of the Cold War. Early in the 1950s, the Soviet Union announced a power reactor program, and by then the British were developing a power reactor fueled with natural uranium that countries without enrichment facilities might want to buy. In both cases Congress feared the U.S. might be left behind. It amended the Atomic Energy Act in 1954 to allow private industry to own and operate reactors, and government-subsidized construction began on a 60,000-kilowatt demonstration plant at Shippingport, Pennsylvania, the same year. The reactor was a Westinghouse Large Ship Reactor, a pressurized-water reactor developed for aircraft carriers.

The PWR configuration met the needs of the U.S. Navy, but it was less than ideal for commercial power. Water was a less efficient but familiar coolant. Uranium oxide, which became the standard light-water reactor fuel, is less dense than uranium metal and conducts heat much less efficiently, but uranium metal swells under neutron bombardment, and reactor designers had not yet had time to figure out how to compensate for the swelling problem in fuel-rod design. Since the light-water reactor isn't a breeder, it wastes most of its fuel; that in turn increases the volume of long-lived radioactive waste. To make their compromise reactor designs competitive in a field dominated by relatively cheap fossil fuels, reactor manufacturers pushed design limits, maximizing temperatures, pressures and power densities. Tighter design limits led to more frequent shutdowns and increased the risk of breakdowns, which in turn required more complex safety systems.

More crucially, manufacturers began pursuing economies of scale by selling larger and larger reactors, without fully addressing the changing cost and safety issues such reactors raised. "The largest commercial facility operating in 1963," two policy analysts write, "had a capacity of 200 megawatts; only four years later, utilities were ordering reactors of 1,200 megawatts."[xxxi] But the safety equipment that government regulators judged sufficient at 200 megawatts they no longer judged sufficient at 1,000 megawatts. So they began requiring further add-on safety systems, escalating engineering and construction costs. Construction time increased from seven years in 1971 to 12 years in 1980, roughly doubling the cost of the plants and raising the cost of the resulting electricity. Nuclear Regulatory Commissioner Peter Bradford would write later that "an entire generation of large plants was designed and built with no relevant operating experience, almost as if the airline industry had gone from Piper Cubs to jumbo jets in about fifteen years."[xxxii] Because of the scale-up in size and the correspondingly larger inventory of fuel, "engineered safety" replaced "defense in depth" as a design philosophy, and it became impossible to demonstrate that large U.S. power reactors were acceptably safe. Nor was a safety culture developed and maintained among the operating teams at private utilities lacking experience in nuclear power operations.

It was these problems, and not antinuclear activism, that led to the cancellation of orders and the halt in construction that followed the Arab oil embargo that began in late 1973. Orders for some 100 U. S. nuclear power plants were cancelled; but orders for 82 coal power plants were also cancelled—nearly 200,000 megawatts cancelled or deferred in all—because the Arab oil embargo stimulated dramatic improvements in energy conservation in the U.S. that stalled a longstanding trend of increasing demand. "Who...would have predicted," Al Weinberg would write, "that the total amount of energy used in 1986 would be only 74 quads, the same as in

1973?"[xxxiii] Today, with demand once again increasing, U.S. nuclear power is thriving: existing plants are being relicensed to extend their operating life another 20 years; plants left unfinished will probably be finished and licensed; and new reactor construction utilizing newer, safer and more efficient designs is almost certainly pending.

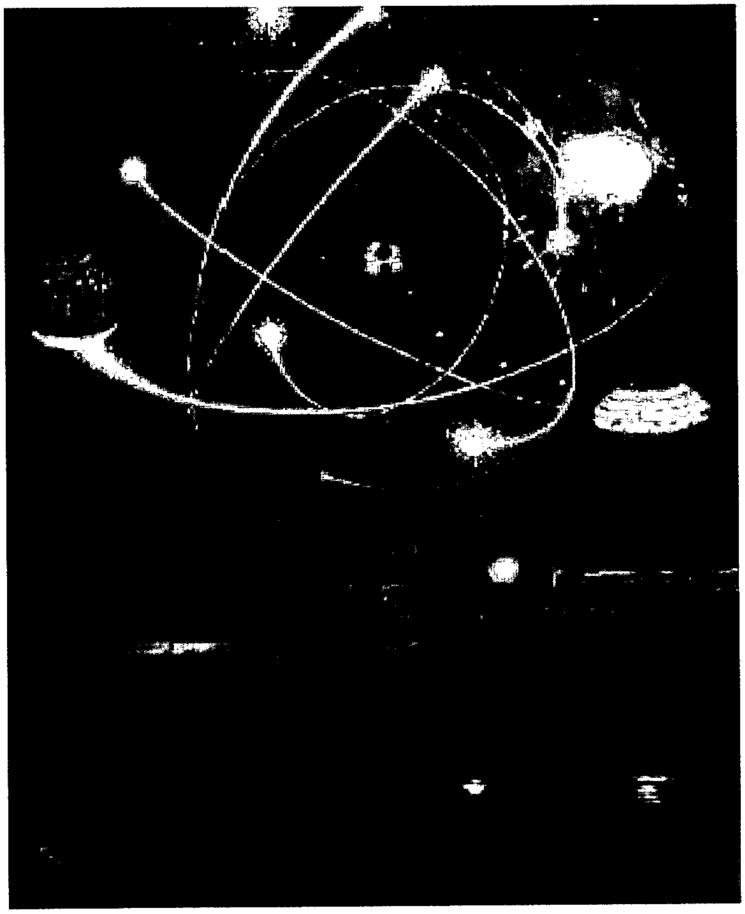
France has a different story, with 80 percent nuclear electricity today, energy security in consequence and air pollution reduced five-fold. Japan is pursuing a highly successful nuclear power enterprise as well. Secrecy extended to nuclear power generation reached a deadly extreme in the Soviet Union. Operators were forbidden to share information about problems and accidents from one plant to the next, making systemic improvements impossible, and information about the developing Chernobyl disaster was delayed for crucial days while Moscow hunkered down. The worst large-scale consequence of Chernobyl has been thyroid cancer in Ukrainian and Belarussian children. I am told by Stanislaw Shushkevich, the first Belarussian head of state and a nuclear physicist, that every Soviet fallout shelter held a supply of potassium iodide that would have protected the children by saturating their thyroid glands, but that Moscow refused to allow the tablets to be distributed until it was too late and the children had already been exposed. I conclude that Chernobyl was a failure not of nuclear power but of the Soviet political system.

A word about public opinion and antinuclear activism. Al Weinberg has argued that nuclear power faltered, in his words, "because nuclear optimists ignored social, political, and economic realities."[xxxiv] I would emphasize the economic part. Almost every nuclear power plant built in the United States was designed for its site rather than prefabricated. These large, expensive plants needed a construction license to build but then had to stand idle while an operating license was negotiated, often with considerable and expensive delays. That mistake has been corrected; one license at the outset now legally covers both conditions. Resistance to nuclear power, such as it was—and every U.S. nuclear power plant that was completed was licensed—was less concerned with risk, with safety, than it was with nuclear power's associations with nuclear weapons, highly centralized political and economic systems and technological elitism. In other words, antinuclearism was primarily a political movement, and proponents of nuclear power missed the point when they defended nuclear power on technical grounds alone. It follows, I think, that controlled thermonuclear fusion is not necessarily exempt from antinuclear attack despite its very different configuration.

On the other hand, the environmental movement has come to challenge with the increasingly solid evidence of global warming. If it doesn't embrace nuclear power, it's left with the technically untenable argument that the carbon buildup can be controlled and reversed by developing renewable energy sources. Anyone who believes that hasn't done the numbers. The problem of global warming should effectively separate real environmentalists from political activists for whom environmentalism has been a cloak. As a harbinger of change, I recently received a copy of a book published in France with the engaging title *Environmentalists for Nuclear Energy,* with an enthusiastic preface by James Lovelock, the research scientist and environmentalist who proposed the Gaia theory. *"I hope it is not too late for the world to emulate France,"* Lovelock writes, "*and make nuclear power our principal source of energy. There is at present no other safe, practical and economic substitute for the dangerous practice of burning carbon fuels.*"[xxxv]

Worldwide across the last decade nuclear power has grown by 30 percent, faster than any other electricity source. In the United States that growth was achieved by increasing efficiency, without building any new reactors at all. There are presently 438 reactors operating worldwide and 36 more under construction. "*Nuclear power has been the cheapest way to produce electricity in the United States for almost the entire decade,*" writes Roger Howsley of BFNL, "*and the trend is for further cost reductions. It is becoming increasingly apparent that when the true external costs of producing electricity are included in the overall economics of power production, nuclear power becomes ever more competitive.*" Howsley confirms that if the true costs of fossil fuel production, including health effects and the economic impact of global warming, were accounted as they are for nuclear power, it would in his words "*double the cost of electricity from coal and increase the cost of gas-generated electricity by 50 percent. By contrast,*" Howsley concludes, "*the cost of nuclear and renewable electricity sources would remain largely unaffected.*"[xxxvi] I disagree with Howsley about renewables, since significant pollution and greenhouse-gas releases result from processing the copious quantities of materials necessary to build their collection systems.

Fusion, if you can make it work, fits in well with these historic trends in energy development. Like nuclear power, it also continues another trend that Grübler and Nakicenovic have identified historically, a trend toward increasing decarbonization, meaning a decrease in the amount of carbon or CO_2 emitted per unit of primary energy consumed.[xxxvii] The carbon intensity of primary energy use today is some 30 to 40 percent lower than in the mid-nineteenth century. The longterm trend toward decarbonization—it averages out to about 0.3% per year—will not be sufficient by itself to limit or reverse the greenhouse buildup, but at least it is moving in the right direction. Solar, wind and



biomass also fit this trend toward decarbonization, but unlike those energy systems fusion is punctiform rather than areal, and the trend has been away from areal energy sources for more than two hundred years. A world solar energy system would require not only a very large and burdensome share of the annual world production of steel, glass and concrete but also and more problematically would require unprecedented levels of international cooperation, because the regions of maximum insolation are distant from major population centers across national borders. We worry about being held hostage by Middle Eastern oil; shouldn't we also worry about being held hostage to Saharan solar electricity? Renewables are also lower-grade energy sources than fusion, another trend in its favor. Grübler and Nakicenovic conclude that *"the persistent and converging trend toward cleaner fuels and lower carbon intensities that seems to accompany economic development is an additional reason for cautious optimism concerning continuing improvements in the future that could assist climate protection efforts."*[xxxviii]

But in truth, as the Economic Law of Life makes clear, we will need every energy source we can find or devise. Coal as it is presently used will no doubt decline in world market share just as the IIASA logistic predicts, but it may find renewal in a new form, as a liquid fuel supplementing petroleum, with the process heat for its liquifaction supplied by nuclear power. That would extend coal's contribution for another hundred years. In the longest run, into the 22nd century, nuclear, fusion and solar electricity and hydrogen fuel promise health, a cleaner environment, an adequate standard of living, a life expectancy of at least 70 years and consequently a minimum of war and civil conflict for a sustainable world population of even ten billion souls. If that sounds like fulfillment of the fundamental human project—the alleviation of suffering through the progressive materialization of the world—well, let's hope.

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Steps Toward the "Hydrogen Economy"[*]

By S.S. Penner

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Abstract We discuss the three different versions of hydrogen use when the primary energy supply is derived from fossil fuels, from fission (breeder) reactors, or from renewable energy sources. The favored energy carrier hydrogen will continue to supply only a minor fraction of transportation energy with continued heavy use of fossil fuels, may become an important market entry in a world with most of the electricity generated in nuclear fission or breeder reactors, and requires new inventions or innovations before significant market entry can occur for hydrogen production from renewable energy sources.

I. Toward the "Hydrogen Economy"

A consensus has emerged during the last few decades that the ideal working fluid for many industrial and transportation applications is hydrogen because its combustion yields water which may then serve as the raw material for recovering the hydrogen and oxygen from which it was formed. The commonly used terminology is misleading because we can envision three different types of hydrogen economies depending on the primary energy-supply source that is used.

Our current industrial system relies on the use of fossil fuels as primary energy source. Based on market selection of the lowest cost source, hydrogen is produced mostly from the fossil fuels natural gas (48% of the total), heavy oils and naphtha (30%) and coal (18%) and by electrolysis (4%) as a by-product of chlorine production.[**] Locations of low-cost electricity supplies provide

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[*] This article represents a part of an invited lecture presented at a meeting of the Western States Section of the International Combustion Institute in San Diego, CA, on 03/25/02.

[**] See IAEA-TECDOC 1085, 03/15/02 on the Internet.

minor additions through electrolysis with electricity generated from fossil or nuclear fuels or at hydroelectric power stations. The hydrogen-production procedures include steam reforming, partial oxidation, as well as plasma pyrolysis, and generally lead to H_2 at year 2000 costs of \$5 to \$15 per GW of hydrogen energy, i.e. costs of about 3 times or more of the current cost of natural gas. The fossil-fuel-based hydrogen economy is currently undergoing rapid changes because the need to minimize air pollution in our urban centers has served to focus attention on the desirability of replacing gasoline- and diesel-powered vehicles by fuel-cell systems. To the extent that this conversion proves to be economically viable, an important step will have been taken in implementing the ideals of the hydrogen economy. During the year 2001, world-wide hydrogen production amounted to about $5 \times 10^{11} m^3$ under standard conditions and thus carried an energy of combustion equaling about 2% of that supplied by fossil-fuel use.**

A second type of hydrogen economy involves the use of nuclear energy as the primary energy-supply source (see Fig. 1). The relatively small low-cost reserves of high-grade uranium suggest that we must plan to use passively safe nuclear *breeder* reactors over the long term. Both conventional fission and breeder reactors require cooling loops with peak temperatures around 1000 to 1200K in the normal cooling cycles. Based on intensive studies performed during the nineteen seventies, we can implement water-decomposition cycles that will produce hydrogen in sequential reaction steps and serve to implement the second type of hydrogen economy that is compatible with effective operation of nuclear reactors as primary energy-supply systems. In our current economies, studies on water-splitting cycles have not progressed to the point where hydrogen production has been demonstrated to be a commercially preferred procedure for transportation applications. However, this deficiency may well be corrected in short order if nuclear (breeder) reactors become the widely used primary energy-supply source.

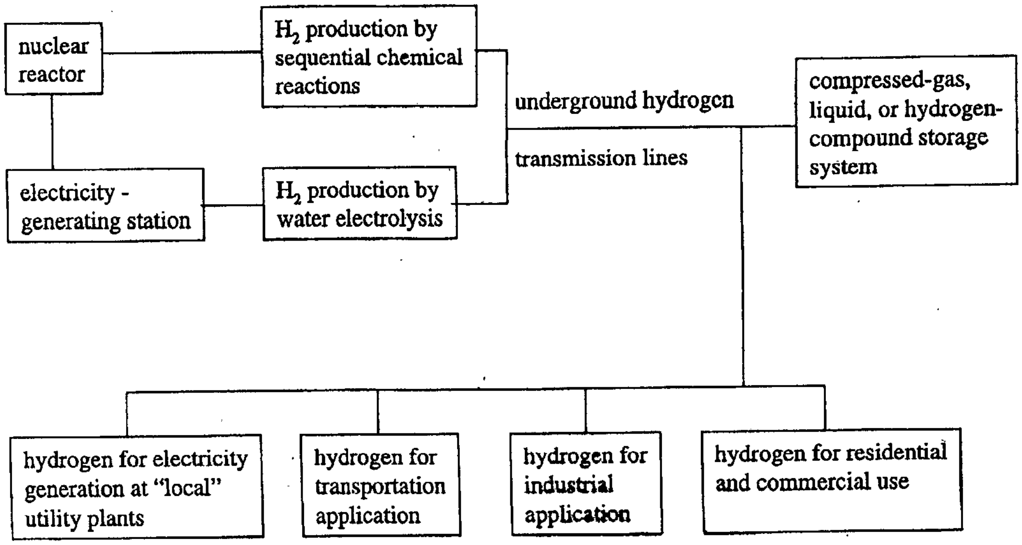

Fig. 1. Schematic of the hydrogen economy using waste heat from a fission reactor.

To a hydrogen-economy idealist, the preceding observations represent heresy. The purist will not accept the continued addition of carbon dioxide to the atmosphere as the result of fossil-fuel combustion and will also not accept the requirements for very long storage of highly radioactive fission products or the possible threat of facilitating nuclear proliferation. To the idealist, successful entry of the hydrogen economy means economically viable hydrogen production using only renewable energy supplies. While the goal of the hydrogen economy has rated very high in terms of the ecology leg of the three components serving as the foundations of our industrialized society (E3 or energy-ecology-economy), it continues to fail in terms of competitive costs and will continue to fail in comparison with primary energy supplies derived from fossil-fuel combustion or nuclear fission and breeder reactors unless a new and low-cost production technology can be developed for making hydrogen.

In the following sections, we review briefly research efforts aimed at hydrogen production from water-splitting cycles and from renewable energy sources. Of these, none has progressed to the point of possible near-term commercial viability without internalizing environmental impacts of fossil-fuel use. However, the complete list of research opportunities (including topics omitted here, such as wind-power systems, photovoltaic power conversion, etc.) is sufficiently varied to lead us to hope for progress even though the last 25 years of subsidized efforts have proven to be sterile.

II. Cycles for Low-Temperature Water Splitting

Methodologies for direct water splitting have been on the drawing board for longer than a quarter century. A vast number of low-temperature thermal cycles have been devised and, to some extent, subjected to empirical implementation for water splitting using the sun or another heat source such as a nuclear reactor as primary input power source. None of these has as yet entered the competitive marketplace. The most promising methodologies are those that couple heat energy provided from nuclear fission reactors to the hydrogen splitting cycle but even these are not likely to compete with direct fossil-fuel utilization even if projected environmental charges are levied for carbon dioxide additions to the atmosphere. An example of these cycles is provided by the Mark 1 cycle invented by C. Marchetti at Ispra in Italy around 1970 (1,2). This cycle is especially compatible with the outflow coolant temperature (~850°C) in a gas-cooled nuclear reactor since the maximum required cycle temperature is only 730°C. The sequential chemical reaction steps for the Mark I cycle are summarized in Fig. 2. The overall process is water splitting according to the process

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2.$$

Although the sequential reaction steps are easily performed, the uses of Hg and HBr constitute significant potential hazards. A cycle that has been studied by German investigators (3a) is shown in Fig. 3 and two cycles currently under investigation in Japan (3b) are shown in Fig. 4. Thirty years after examination of many thousands of potential sequential water-splitting steps and a great deal of experimental work, no commercially viable design has been devised for our fossil-fuel-dominated economic system. Recent discussions of work of this type may be found in Refs. (3a and b) but are mostly based on studies performed during the nineteen seventies. Of special interest in this connection is the calcium-bromine-iron cycle which has been under development in Japan since 1978 under the name UT-3 cycle with a maximum temperature of only about 1000K (see Fig. 4).

$$CaBr_2 + 2\,H_2O \xrightarrow{730°C} Ca(OH)_2 + 2\,HBr \qquad \text{(water-splitting reaction),}$$

$$Hg + 2\,HBr \xrightarrow{250°C} HgBr_2 + H_2 \qquad \text{(hydrogen-switching reaction),}$$

$$HgBr_2 + Ca(OH)_2 \xrightarrow{200°C} CaBr_2 + HgO + H_2O \qquad \text{(oxygen-shifting reaction),}$$

$$HgO \xrightarrow{600°C} Hg + (1/2)O_2 \qquad \text{(oxygen-switching reaction),}$$

The overall process is

$$H_2O \longrightarrow H_2 + (1/2)O_2.$$

Fig. 2. The MARK-1 cycle invented by Marchetti around 1970.

$$3\,FeCl_2 + 4\,H_2O \xrightarrow{450\text{-}750°C} Fe_3O_4 + 6\,HCl + H_2,$$

$$Fe_3O_4 + 8\,HCl \xrightarrow{100\text{-}110°C} FeCl_2 + 2\,FeCl_3 + 4\,H_2O\,,$$

$$2\,FeCl_3 \xrightarrow{300°C} 2\,FeCl_2 + Cl_2\,,$$

$$Cl_2 + Mg(OH)_2 \xrightarrow{50\text{-}90°C} MgCl_2 + (1/2)\,O_2 + H_2O\,,$$

$$MgCl_2 + 2\,H_2O \xrightarrow{350°C} Mg(OH)_2 + 2\,HCl\,.$$

The overall process is

$$H_2O \longrightarrow H_2 + (1/2)\,O_2\,.$$

Fig. 3. The AGNES cycle studied in Germany.

Fig. 4. Two cycles studied in Japan.

SULFUR-IODINE CYCLE

$$xI_2 + SO_2 + 2\,H_2O \longrightarrow H_2SO_4 + 2\,HI_x \qquad (370\ K),$$

$$2\,HI_x \longrightarrow H_2 + xI_2 \qquad (393\ K),$$

$$H_2SO_4 \longrightarrow H_2O + SO_2 + \tfrac{1}{2}O_2 \qquad (1144\ K).$$

CALCIUM-BROMINE-IRON CYCLE

$$CaBr_2\,(s) + H_2O\,(g) \longrightarrow CaO\,(s) + 2\,HBr\,(g) \qquad (998\ K),$$

$$CaO\,(s) + Br_2\,(g) \longrightarrow CaBr_2\,(s) + \tfrac{1}{2}O_2\,(g) \qquad (823\ K),$$

$$Fe_3O_4\,(s) + 8\,HBr\,(g) \longrightarrow 3\,FeBr_2\,(s) + 4\,H_2O\,(g) + Br_2\,(g) \qquad (523\ K),$$

$$3\,FeBr_2\,(s) + 4\,H_2O\,(g) \longrightarrow Fe_3O_4\,(s) + 6\,HBr\,(g) + H_2\,(g) \qquad (848\ K).$$

III. Direct Water Photolysis using a Semiconductor

During the seventies of the last century, there was a brief flurry of excitement about direct water photolysis using an electrochemical cell (see Fig. 5) as first described (4a) in 1972 for a TiO_2 n-type semiconductor. In brief, the system consisted of an n-type semiconducting TiO_2 (rutile) electrode exposed to sunlight and connected to a platinum electrode. The TiO_2 was mounted on an indium plate which served as electrode-contact material. When the TiO_2 was exposed to light, electrons and holes (p^+) were formed (see Fig. 6) according to the process $TiO_2 + 2h\nu \rightarrow TiO_2 + 2e^- + 2p^+$, which led to hydronium-ion and gaseous oxygen formation at the negative electrode according to the reactions

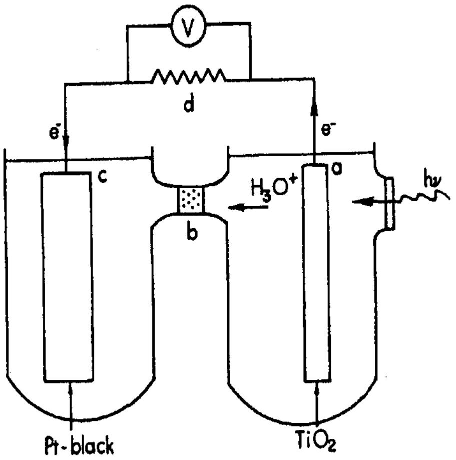

Fig. 5 Schematic of the electrochemical cell in which a TiO_2 electrode is connected with a platinum electrode. The surface area of the platinum-black electrode used was approximately 30 cm². The symbol a refers to a TiO_2 semiconductor mounted on an indium plate, which serves as an electrode contact material. The TiO_2 is exposed to light ($h\nu$). The symbol d describes an external load across which the voltage was measured with a voltmeter V. The symbol c refers to a platinum-black electrode, while b describes a suitable electrolyte. The following processes occur in the gaseous (g) and liquid (ℓ) phases:

$$TiO_2 + 2h\nu \rightarrow TiO_2 + 2e^- + 2p^+,$$

$$\left.\begin{array}{l} 2p^+ + H_2O(\ell) \rightarrow (1/2)O_2(g)\uparrow + 2H^+, \\ 2H^+ + 2H_2O(\ell) \rightarrow 2H_3O^+(\ell), \end{array}\right\}$$

$$2e^- + 2H_3O^+(\ell) \rightarrow H_2(g)\uparrow + 2H_2O(\ell),$$

$$H_2O(\ell) + 2h\nu \rightarrow H_2(g) + (1/2)O_2(g).$$

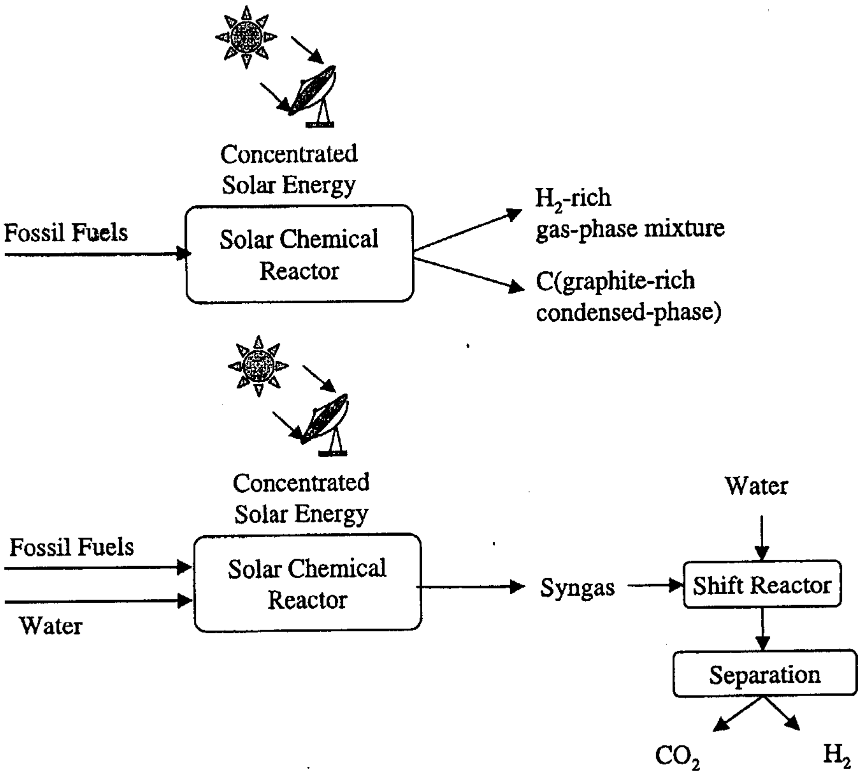

Fig. 6. Solar processing of fossil fuels to reduce the energy requirements from fossil-fuel combustion (after Steinfeld et al, Ref. 6).

$$2p^+ + H_2O(\ell) \rightarrow (1/2)O_2(g)\uparrow + 2H^+,$$
$$2H^+ + 2H_2O(\ell) \rightarrow 2H_3O^+(\ell).$$

The electrons pass through an external circuit and then produce hydrogen at the positive electrode according to the reaction

$$2e^- + 2H_3O^+(\ell) \rightarrow H_2(g) + 2H_2O(\ell).$$

The current densities were observed to become constant at different values for different levels of the pH. For a 500-W xenon lamp, the quantum efficiency was claimed to be about 0.1 with a cell emf of 0.5 volt. TiO_2 is not an optimal semiconductor for water splitting because its band gap between the valence and conduction bands is about 3eV $(\text{light wavelength } \lambda < 4{,}150\text{A})$ whereas electrochemical water splitting can be accomplished at 1.25 eV $(\lambda < 10{,}000\text{A})$. Thus, with an optimally chosen semiconductor, it was expected that the water-splitting efficiency could be increased by about a factor of 4.55 for a 6000°K blackbody light source like the sun.

Using a multi-band gap photoelectrochemical system (PEC) in an arrangement otherwise similar to that applied in 1972, an efficiency of 12.4% was claimed in a 1998 publication (4b). Capital cost and O&M charges for a commercial prototype have not yet been specified. This line of investigation is expected to be continued in the future.

IV. Direct Water Photolysis in a Homogeneous Phase

A new approach to water splitting was published in August 2001 (5) and falls appropriately into the category of direct water photolysis using photochemistry. The procedure is very different from that used in the attempts to drive the water-splitting reaction by using two photons absorbed on a transition-metal complex. With the proposed procedure, hydrogen is produced in solution by employing a mixed-valence dirhodium compound which, on exposure to a photon flux, breaks two rhodium bonds of a core molecule in the presence of a halogen trap to regenerate the original rhodium compound (catalyst), which may thus be reused to react with more water and produce more hydrogen. For details referring to the photochemical processes and the nature of the chemical rhodium complexes involved, reference should be made to the original publication by Heyduk and Nocera (5). A plot of number of 10^{-4} mole of H_2 produced as a function of time shows production of up to about 1.0×10^{-4} mole of H_2 after about 5 hours of illumination using uv-to-visible light with wavelengths above 338 nm. Thereafter, the rate of hydrogen production is reduced and about 13 hours of exposure were required to reach 1.3×10^{-4} mole of hydrogen output. Much work remains to be done before this type of approach merits a practically meaningful appellation as a process for producing hydrogen from photons, not only because the efficiency of water splitting is very low but also because the procedure produces an accumulation of halogen from a halic acid that is required in the photochemical reaction.

1) Fossil-Fuel Processing Augmented by Solar Energy

Solar processing (6) of fossil fuels to produce hydrogen (see Fig. 6) is another potentially useful approach because the energy absorbed from the sun may represent a low-cost addition to the energy of combustion of the fuel. This approach has been advocated (6) as a reasonable *intermediate* step between our presently used fossil-fuel-based technologies and the goal of a hydrogen economy based on the use of renewable energy inputs. The thermal decomposition (pyrolysis) with the production of solid carbon for any hydrocarbon of composition C_xH_y may be represented by the overall reaction

$$\text{solar energy} + C_xH_y \rightarrow xC_{\text{solid}} + (y/2)H_2.$$

Similarly, steam reforming of the hydrocarbon C_xH_y to produce CO with solar energy input is described by the overall reaction

$$\text{solar energy} + C_xH_y + xH_2O \rightarrow [(y/2) + x]H_2 + xCO$$

The endothermic processes to produce H_2 from fossil fuels represent established practice for energy supplied from fossil-fuel combustion rather than from the sun. The solar approach may have the following advantages: (*i*) hydrogen is produced with reduced utilization of heat release from combustion of the hydrocarbon feedstock, (*ii*) in the special case when solid carbon is produced and efficiently sequestered, no oxidized carbon compounds are emitted, (*iii*) the caloric content of the fuel is upgraded by the solar energy input. The suggested approach requires quantification in terms of costs. Environmental purists will object to the utilization of fossil fuels in what is supposed to become a totally renewable and sustainable energy technology. If this methodology is adopted, the value of the by-product graphite will decline rapidly because chemicals produced as by-products of energy-conversion technologies will soon become available in large oversupplies.

VI. Fuel Production Using Ocean Thermal Energy Conversion (OTEC)

Another solar processing procedure depends on OTEC and involves the use of this large resource from the tropical oceans. An excellent summary of OTEC has recently been published by W.H. Avery (7) and contains an optimistic conclusion concerning sea-based production of methanol from coal on an OTEC platform or production of ammonia from water electrolysis followed by hydrogen reaction with atmospheric nitrogen. Because of high hydrogen transmission costs for substantial distances, the use of condensable fluids is preferred over sea-based production of gaseous compressed hydrogen. Since the ultimate purpose of the hydrogen economy is the production of non-polluting fuels without carbon dioxide addition to the atmosphere, the ammonia cycle is preferred. According to Avery (7), cost reductions for ammonia below gasoline and diesel-fuel costs may be achieved with specified OTEC systems after a learning period. The direct use of ammonia in the transportation sector will probably be judged to be too hazardous and land-based reprocessing of ammonia to hydrogen, followed by direct use of this fuel in fuel-cell systems, is likely to be the preferred approach. It should be noted that OTEC development enjoyed support from the US Department of Energy and from the French and Japanese governments to the extent of about $250 million until about 1995, when the development status was judged to be ready for entry by for-profit concerns. Although this last step has not yet materialized, it is likely to occur with significant escalation of fossil-fuel prices or with the passage of laws internalizing (i.e. charging consumers) the projected environmental costs of continued fossil-fuel use. In summary, it is likely that OTEC production of hydrogen-containing fuels will serve as one of several preferred approaches to commercial realization of the hydrogen economy using only renewable energy sources.

It has been demonstrated in various parts of the world (the Caribbean, near Hawaii, off-shore Taiwan) that OTEC systems facilitate the growth of mariculture by bringing nutrients from deep water layers to support increased populations of fish near the sea surface. This added benefit should further reduce the market-entry costs of OTEC-based fuel production.

VII. Hydrogen Utilization

Widespread uses of hydrogen should not represent a major challenge. What we know will work is the low-cost application of hydrogen in oxidation processes of various types for electricity generation, transportation applications (including flight systems), home heating, etc. in spite of residual fears attributable to the "Hindenburg Syndrome" that has many non-believers convinced that extensive use of hydrogen as a working fluid is more hazardous than the parallel activity utilizing oil or gasoline or natural gas.

The inevitable conclusion that may be drawn from the preceding summary remarks is the still not answered challenge to the research community to learn how to make hydrogen at greatly reduced costs from a low-cost primary supply source (preferably water) while using "free" or low-cost energy supplies. This goal has proved to be an elusive research challenge for many years but a challenge that must be met before we will see the promise of a hydrogen economy for an affluent world population.

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Better Days Ahead for the U.S. Fusion Program?

By Scott Nance

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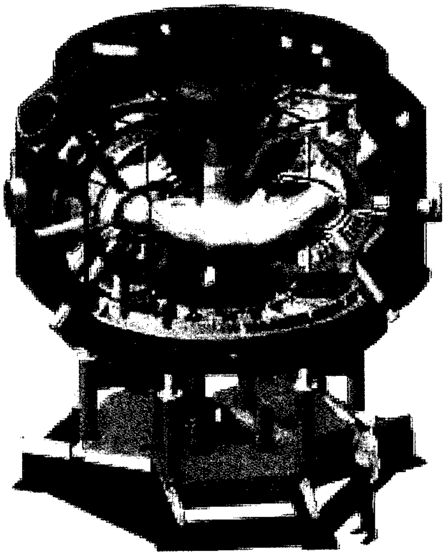
After years of declining budgets, the hardest times finally may be ending for the U.S. nuclear fusion research community. But those in the field still have some big questions to answer that could determine the future of fusion science.

Scientists have for decades tried to harness the atomic process that powers stars as a new, ready energy source, achieving only limited success to date, with even fusion's most ardent supporters acknowledging that commercial fusion energy is decades away. At the same time, fusion funding has fallen dramatically over the years, with the fusion budget at the Department of Energy-the largest funder of U.S. fusion science, dropping from a high of $469 million in 1984 to $217 million in 1999.

Funding has rebounded somewhat in the last few years, with current spending set at $247.5 million, and the Bush administration appears ready to treat fusion science more favorably. But U.S. fusion scientists and administration officials have to decide a course for what many see as the next large, logical step in fusion research--a so-called burning plasma experiment, and U.S. participation in the International Thermonuclear Experimental Reactor (ITER) project. The future of the field could ride on how that decision plays out, according to one prominent researcher.

The Bush administration is offering fusion researchers several carrots this year. It has proposed a modest, $10 million increase to DOE's fusion budget for fiscal year 2003. It also has proposed moving ahead with a significant new fusion experiment at the Princeton Plasma Physics Laboratory (PPPL) a $69 million project knows as the National Compact Stellarator Experiment (NCSX).



PPPL's National Compact Stellarator Experiment (NCSX).

In addition, the administration supports expanding the operating time at three national fusion user facilities. In his fiscal year 2003 budget proposal, President Bush has included $111 million which is aimed at reversing the trend of declining facility operating time, said Raymond Orbach, the new director of DOE's Office of Science. The administration's budget would expand operations at the DIII-D tokamak at General Atomics in San Diego, the Alcator C-Mod tokamak at the Massachusetts Institute of Technology and the National Spherical Torus Experiment at PPPL, Orchach said.

The budget cuts of recent years created an amount of anguish and concern among U.S. Fusion researchers, but they ultimately made the research community stronger, said Charles C. Baker, Director of the Virtual Laboratory for Technology at the University of California, San Diego, and a member of the federal Fusion Energy Sciences Committee (FESAC) which provides DOE with input into the direction of the fusion program.

"I think we have weathered [the budget cuts] reasonably well, and one sign of that is now a [proposed] modest improvement in the budget," he said. "But maybe more important than that, I think the underlying attitudes of the researchers are generally on the positive side."

The budget woes "created a renewed sense that we're putting the right emphasis on the science and the underlying technology," Baker added.

Fusion scientists made important advances in understanding very hot plasmas, according to Robert Goldston, director of PPPL. "The quality of our science has taken kind of a quantum leap in about the last five years," Goldston said. "...The level of scientific understanding of these systems is just qualitatively different in the last five years." Goldston disputed the notion that fusion scientists had in the past overpromised the potential of fusion to generate power. He cited the history of the Tokamak Fusion Test Reactor at PPPL, which ultimately produced more than 14 orders of magnitude more energy than it originally produced in 1974. "While we went up by 14 orders of magnitude, computer chips went up by five orders of magnitude, and people think computer chips did pretty well," he said.

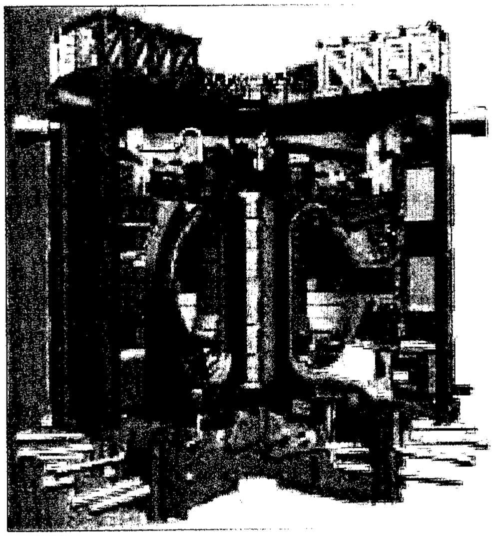
But fusion scientists also went through a lot of soul-searching in recent years as they saw their funding dwindle, prompting a look at whether other fusion designs should be investigated beyond the tokamaks traditionally used to generate fusion, according to Bill McCurdy, a FESAC member and associate director for computing sciences at Lawrence Berkeley National Laboratory. That, in turn, led to a fresh look at an old idea to create fusion that is known as a stellarator. Stellarators date back to the 1950s and consist of highly complex magnetic structures that produce twisted magnetic fields, but represent "much harder geometry and a much more complicated situation to model" than tokamaks, McCurdy said.

"In order to design those, and to explore the experimental space of possibilities, large-scale calculations and a much more focused theory effort than they've had in the past will be necessary," he said.

The compact stellarator proposed for PPPL is a design that should hold on to heat very well, should be very stable, and should run steadily without any power required to sustain the plasma, "which would be an amazing result if we can pull it off," Goldston said. Stellarators offer an important advantage, Goldston said. "Tokamak, you have to stand on your head a little bit and you have to drive them to make them run steadily, whereas stellarators run naturally steadily--it's sort of a fundamental property," he said. The stellarator at PPPL would be operational in 2007. Another stellarator has been proposed at Oak Ridge National Laboratory using a different design.

The NCSX experiment at PPPL will likely yield important new science, but most agree the next large step the fusion community must take is a burning plasma experiment--actually igniting using a fusion plasma. Achieving a burning plasma is critical if fusion is to be an energy source, Baker said. "It's not a question of whether you go through it, it's [a question of]what's the right time and the right configuration and type of experiment to be done," he said. Most scientists feel they are at a stage where they are technically ready to do a burning plasma experiment, and achieving a burning plasma would allow for substantial net energy gain, Baker said.

The ITER program, which involves the European Union, Russia, Japan and Canada, is the most prominent attempt at a burning plasma. The United States had been a part of ITER until 1999, when the Clinton administration withdrew U.S. participation largely for cost reasons.



International Thermonuclear Experimental Reactor

FESAC comissioned a panel in February to look at a brining plasma experiment, with a study ongoikng within the research community culminating in a workshop this summer in Snowmass, Colorado.

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FOOTNOTES: "Energy Transitions: A History Lesson"

[i] Paraphrased from Scarry (1985), p. 278ff.

[ii] IIASA (1981), p. 100.

[iii] Grübler (1991), p. 159, p. 163.

[iv] IIASA (1981), p. 100. Cf. graph on p. 101; slide updates graph with information from Cesare Marchetti (Denis Beller, LANL, personal communication, 2000).

[v] Marchetti (1987b), p. 387.

[vi] Brimblecombe (1987), p. 35.

[vii] Brimblecombe (1987), p. 30.

[viii] Brimblecombe (1987), p. 30.

[ix] Wrigley (1994), p. 94.

[x] Wrigley (1994), p. 94.

[xi] Wrigley (1994), p. 11.

[xii] Wrigley (1994), p. 6.

[xiii] Wrigley (1994), p. 8.

[xiv] Landes (1994), p. 108.

[xv] Samuel (1994), p. 198.

[xvi] Quoted in Yergin (1991), p. 28.

[xvii] Pratt (1981), p. 17.

[xviii] Nakicenovic (1986), p. 313.

[xix] Quoted in Rhodes (1999), p. 35.

[xx] Thompson (1994), pp. 282-283.

[xxi] Nakicenovic (1986), p. 316.

[xxii] Nakicenovic (1986), pp. 316-317.

[xxiii] Pratt (1981), p. 18.

[xxiv] Pratt (1981), p. 317.

[xxv] Cottrell (1955), p. 107.

[xxvi] Pratt (1981), Table 1, p. 10.

[xxvii] Marchetti (1987a), p. 160.

[xxviii] Marchetti (1987b), p. 390.

[xxix] Marchetti (1987a), p. 166.

[xxx] My discussion of the history of nuclear power is drawn from Rhodes (1993).

[xxxi] Joseph Morone and Edward Woodhouse, quoted in Rhodes (1993), p. 44.

[xxxii] Quoted in Rhodes (1993), p. 45.

[xxxiii] Weinberg (1990), pp. 212-213.

[xxxiv] Weinberg (1990), p. 219.

[xxxv] Lovelock (@001), p. 21.

[xxxvi] Howsley (2002), p. 21.

[xxxvii] Cf. Grübler and Nakicenovic (1996); Nakicenovic (1996).

[xxxviii] Grübler and Nakicenovic (1996), p. 106.

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