Energy and Technology Review

Lawrence Livermore Laboratory

March 1977

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THE COVER

The red-hot electrode is the collector of an experimental direct energy converter capable of extracting 2 kW of electrical power from a 15-keV beam of H^+ ions. The electrode is made of molybdenum and cooled by radiation only. A mixed beam of ions and atoms enters from the right, passes first through a grounded aperture, and then through a negative electrode that turns back free electrons in the beam. Space charge then spreads out the ion beam so that it strikes the collector electrode, operated at high positive potential to slow the ions and convert most of their kinetic energy into electrical potential energy before they hit. This slowing down is only partly effective; the excess kinetic energy heats the electrode and is eventually recovered in a coolant cycle or dissipated as radiant energy. The neutral atoms in the original beam pass unaffected through all the electrodes and then may be injected into a mirror fusion experiment or reactor.

ABOUT THE JOURNAL

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The *Energy and Technology Review* is published monthly to report on accomplishments in this energy and environmental research and on unclassified portions of the weapons program. A companion journal, the *Research Monthly*, reports on weapons research and other classified programs. Selected titles from past issues of the *Energy and Technology Review* are listed opposite the inside back cover.

March 1977

Energy and Technology Review

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BRIEFS

The short items on this page announce recent developments of importance. Some of these items may be amplified in future issues; none of this material is reported elsewhere in this issue.

TWO-PHASE EQUATION OF STATE FOR WATER

For reactor loss-of-coolant safety calculations, we needed an accurate two-phase equation of state (EOS) for water. Typical continuous-function representations of the water EOS lack precision; they are unable to follow the abrupt changes in properties across a phase boundary. We have constructed a preliminary two-phase EOS that has the required precision.

Our water EOS is based on a soft-sphere theory of liquids that has proved useful in modeling molecular and metallic liquids. In such a theory, the energy of a pair of molecules increases smoothly as the distance between the particles decreases. In the less realistic hard-sphere theory, the particles are impenetrable. The energy increases abruptly to infinity at a fixed interparticle distance.

Constructing a complete two-phase EOS means accurately fitting the density-temperature liquid-vapor coexistence curve. We started by fitting two points on this curve: the critical point (where the liquid and vapor phases coalesce) and normal density. Figure 1a shows the resulting fit. Another accurate fit to the critical pressure brought the pressure-temperature coexistence curve (Fig. 1b) close to experimental data.

The value of the new preliminary EOS model is the precision with which it represents the way thermodynamic functions change abruptly going from the liquid to vapor phase. Its disadvantage is the time it takes on the computer. The next step will be to improve its efficiency.

Fig. 1. Liquid-vapor coexistence curves for water: (a) temperature-density and (b) pressure-temperature. Solid curves are the best soft-sphere fits; dashed curves are experimental data. Both curves in (b) end at critical pressure points.

CONSERVATION

Transportation's Role in the Energy Problem

Transportation poses the most critical challenge to the nation's energy research and development. Unlike other energy-consuming sectors of the economy (industrial, residential, and commercial), it is almost totally dependent on oil. It is also an inefficient energy user with potential for large efficiency gains. These facts, combined with the limited potential of mass transit and the likelihood that the automobile will remain the public's chosen mode of travel, put a premium on transportation research and development. Within the next 25 years, both domestic and world oil reserves will begin to run out, and alternate energy sources for transportation will then be necessary. LLL

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is currently involved in a number of research programs — on both the supply and end-use sides of the picture — to reduce transportation's role in the nation's energy problem.

Perceptions of the nation's energy problem and of the needs for energy research and development have gone through a series of changes. Even before the Arab oil embargo, many groups recognized the coming energy problem, but the only government group to pursue a solution was the Atomic Energy Commission with its reactor program.

When the embargo took place, the Federal government as a whole swung into action. Both the Federal Energy Administration and the Energy Research and Development Administration were created. Research and development on the supply side of the energy problem were initially emphasized.¹ Since the cost of synthetic fuels was thought to be

less than or at most equal to that of imported oil, rapid development of these fuels was a key element of the nation's energy policy. A year later, improved efficiency – and therefore reduced end-use demand – was given priority, though it was not clear what measures would be most effective in improving end-use efficiencies.²

The seriousness of the energy problem is perhaps just beginning to sink in, however. By the end of 1977, the effects of the jump in the price of imported oil will have cost about \$750 per U.S. household annually and perhaps a total of two million jobs. Out of an appreciation of this linkage between energy costs and the economy, as well as of the fact that synthetic

fuels are not yet competitive, has come the belief (or hope) that mandatory conservation is the way to solve the energy problem. But how far the American public is willing to go in conservation is still unknown.

It is against these changing perceptions of the energy problem that we present the following assessment of what technological research and development can do to help. At the same time, we recognize that social and economic issues are crucial elements in the problem's solution, too.

The energy flow diagram shown in Fig. 1 displays the critical elements of the nation's energy problem. Most important are the increasing oil imports, which are required due to dwindling domestic petroleum and

Fig. 1. U.S. energy flow for 1976. Primary resource consumption (defined as resource inputs minus exports) was about 72.1 EJ (72.1 quads). Transportation was the most dependent on petroleum and the least efficient end-use sector. It thus poses a major challenge to research and development aimed at solving the nation's energy problem.

natural gas production. During recent months, these imports exceeded domestic production for the first time.

On the demand side of the problem, the flow diagram shows that transportation is the least efficient end-use sector. In addition, it is almost totally dependent upon oil, unlike the other end-use sectors that have existing fuel alternatives. In our judgment, the transportation sector — from both the supply and the demand sides — poses the most critical challenge to energy research and development in this country.

THE TRANSPORTATION PROBLEM

Figure 2 outlines the nature of the transportation problem. Highway vehicles account for 75% of transportation energy. The railroads have been losing their market share, while the airplane is increasing its share. "Other" refers to energy required by barge and pipeline. Clearly, the place to start doing something about transportation energy is among highway vehicles, particularly automobiles, because they use the most energy.

Figure 3 shows the efficiencies of various forms of travel. Airplanes use the most energy in terms of Btu per person-mile, mainly because they operate only 49% full. If they traveled 75% full, they would have about the same energy intensiveness as the standard automobile with its average 1.9 passengers. The small car is, of course, more efficient, but the intercity bus is the most efficient with its average load of 22 passengers.

The urban bus runs with 10 passengers on the average, and the urban rail car operates at about 25% capacity. At these load factors, the small car is about as efficient as the urban bus. The question is whether load factors could be increased, and what the effect would be.

The fraction of the populace using mass transit for work trips is plotted against population density in Fig. 4. In New York City, which is off the graph, 47% use mass transit because of the high population density and the inefficiency of any other transportation mode. No other city approaches this figure, and the trend

Fig. 2. Energy usage among various transportation modes. The nature of the transportation problem is evident in the dominance of highway vehicles: in 1973, automobiles and trucks accounted for 75% of energy usage. Highway vehicles, and especially the automobile, are thus the likely starting point in any solution to the transportation problem.

is for lower transit usage as population density declines. This is understandable: as people spread out, it becomes less convenient to reach the transit stations and more expensive to run the system.

Although some cities could update their transit systems in an attempt to double their usage — and this should be done — the disturbing point here is that only 5 to 15% of the people in a given city use mass transit. Thus a doubling would have little effect on the total transportation problem.

The potential for mass transit is also limited by American living patterns. Most people live and work in our urban areas: 38% live and work in the central city, 36% live and work in the urban ring, 19% commute into the central city, and 7% commute out.³ Thus the concept of the urban ring being totally a bedroom community is not true.

Fig. 3. Energy intensiveness for various transportation modes. Small cars have energy costs comparable to other efficient travel modes, such as mass transit. With an average load of 22 passengers, the intercity bus is the most efficient. Mass transit (both bus and rail) could become still more efficient if its load factors were greater. Its potential is limited, however, because relatively few people can use it.

Fig. 4. Use of mass transit for work trips in urban areas. Even in the more densely populated cities, public transportation's potential is limited. In general, only 5 to 15% of the city's work force commute to work on mass transit, and only about 45% of the nation's work force live in the city. Even doubling the usage rate, therefore, would do little to alleviate the transportation problem.

Most Americans choose to live reasonably close to work. The urban ring has shopping centers, manufacturing plants, service industries, and offices, and most of the people who live there work there. The conclusion, therefore, is that upgrading public transportation in the central city (where it might be effective), even if everybody used it, could affect only 38% of all work trips.

The work trips we have been discussing constitute about 39% of automobile usage; family business (i.e., medical, shopping, and other uses) constitutes another 18%; education, civic, and religious uses constitute 6%. Thus nearly two-thirds of automobile usage supports the business of living; social activities and recreation account for the other third. Cutting down on automobile use without reducing our standard of living will be hard.

Taken together, then, mass transit plays an essential role in the central city. At the same time we must remember that every mass transit system in the world is publicly subsidized. Most Americans prefer to live

in open areas unsuitable for mass transit. They also enjoy the freedom of their private automobiles. All of these factors conspire against solving the nation's transportation problem by mass transit alone. We must conclude that the potential for public transit is limited and that the demand for automobiles will remain.

On the supply side of the problem, we have already remarked that transportation is almost totally dependent on oil. The domestic oil picture is shown in Fig. 5. From 1950 to 1973, oil demand rose sharply at a rate of 3.8% per year; then the embargo hit, the recession occurred, and with higher oil prices we have a new situation. We cannot foresee what demand will be over the next 25 years, but for illustrative purposes we have plotted two curves: a low demand increasing at 1.8% per year (about half the preembargo rate) and a demand determined by holding per-capita use constant so that total demand rises only because of population growth.

On the supply side we have estimated that 34 billion tonnes (250 billion barrels) of oil are yet to be

Fig. 5. Projected domestic oil supply and demand for the next 50 years. We estimate that the U.S. has about 34 billion tonnes (250 billion barrels) of producible crude oil; the inclusion of natural gas liquids increases this supply some. Estimates of future demand, however, far outstrip even the combined supply, especially after production peaks around 1990-2000. The resulting supply/demand gap can be closed only by developing alternative energy sources, since we expect world oil production to peak in the same decade (Fig. 6), limiting the availability of imports.

Fig. 6. World oil reserves are also limited; by our estimates, production will peak around 1990-2000. Thus oil imports offer no long-term solution to the transportation problem. Within the next 25 years the world's oil will begin to run out, and other energy sources will be required.

produced. This is an optimistic figure based on the National Petroleum Council estimates of undiscovered resources and on our estimates of recovery factors. The rise starting in 1977 is, of course, due in large part to the flow of Alaskan oil. Nonetheless, domestic production appears to peak out in the 1990-2000 time frame, and the gap between domestic supply and demand grows extremely rapidly thereafter. In principle, this gap could be supplied for a while by importing more oil, but estimates of world oil production also show a peaking around 1990-2000 (Fig. 6).

For the last 50 years, we have lived with petroleum as our prime fuel. It was cheap, convenient, and relatively clean. We must face the fact, however, that within the next 25 years the U.S., as well as the rest of the world, will begin to run out of oil, and alternate energy sources will be necessary.

The end-use sector most affected by this fact is transportation. The residential, commercial, and industrial sectors, as well as the electric power industry, all have existing alternatives, but not so for transportation. In the short span of 25 years, the transportation system as we know it today must be well on its way to being totally changed. Alternate fuels must be found to alleviate its complete and

vulnerable dependence on petroleum. Other propulsion systems must be developed to provide ways of powering vehicles other than through the use of liquid fuels.

In the near term, we need more efficient and environmentally acceptable heat engines optimized to conserve petroleum. In the long term, we must prepare for the post-petroleum era when petroleum-derived liquid fuels for powering our vehicles will no longer be available. Furthermore, the time required to develop and implement solutions is about the same as the time remaining until world oil production peaks.

R&D SOLUTIONS

The nature of the research and development solutions is becoming clear. For alternate fuel systems, since we have to make a change, we ought to change to an optimized fuel/engine system, and not simply assume that synthetic gasoline made from coal or shale will suffice. There are two leading candidates that need to be examined in detail: broad-cut fuel and methanol.

Broad-cut fuel has a wide boiling range (100 to 650°F). It should be cheaper and more efficient to manufacture than synthetic gasoline. On the other

hand, it will require a continuous combustion engine, such as the turbine or Stirling engine, or a fuel-injected engine like the stratified charge. A central question of such a system is emissions: what will they be, and will they be sufficiently low?

The second candidate system is methanol. Methanol burns cleanly, and high-compression engines that are more efficient than engines running on synthetic gasoline can be used with methanol.⁴ The problem is one of cost. If *in situ* coal processing can be made technically successful, then perhaps a methanol system would be distinctly advantageous.

An alternative to liquid fuels is electric propulsion. The problem here is that we lack a powerful enough battery. Flywheels can be used to extend the range of electric vehicles, and perhaps an auxiliary internal combustion engine can also do the same. Ultimately, however, a good battery is needed.

LLL RESEARCH

LLL currently has research projects bearing on the transportation problem. On the supply side, we have an *in situ* oil-shale project aimed at making synthetic fuel from the vast oil-shale deposits in Colorado.⁵ *In situ* retorting has the potential for less environmental impact, less water usage, and a lower cost than any of the surface mining and retorting processes.

The Laboratory's *in situ* coal gasification project⁶ also has a bearing on the transportation problem, because the gases that are produced (CO , H_2 , C_2H_4) can be processed into methanol. If this *in situ* process can be developed, it promises lower cost conversion of coal to gas compared with any of the mining and surface processing methods. It may even be possible to develop an underground liquefaction process for coal.

On the end-use side of the problem, the Laboratory has a combustion program in which we are applying skills developed in our weapons work on computer modeling of hydrodynamic and kinetic processes to study combustion in an automobile engine. This computer modeling will be verified with our diagnostic capabilities and is being done in conjunction with

General Motors Corporation to give a context of practicality.

A second end-use technology under study is flywheel development. Flywheels must be made exceptionally strong if they are to store large amounts of kinetic energy in a small space. Again, from weapons technology, we have developed fiber-composite materials with exceptional strength. When used in flywheels, these materials may be able to increase the performance and double the range of electric vehicles. Range is, of course, the primary limiting factor in a practical electric vehicle. The concept of using a flywheel to extend range has been adapted by Garrett AiResearch and will be incorporated into prototype vehicles being produced under ERDA contract.⁷

A third end-use research project involves the lithium-air battery. This new class of battery was invented at Lockheed and promises automobile performance comparable to that of the internal combustion engine. Much research remains to be done, however, and Lockheed has asked the Laboratory to participate in a joint research project now under way with EPDA.⁸

In addition to these five technology projects, we are also carrying out three ERDA-funded system studies. The first involves alternate fuels planning: developing a research and development strategy for making the transition to synthetic liquid fuels (see following article). The second is a study of regenerative braking for electric and hybrid vehicles. The concept of taking the energy normally wasted in the heat of braking and putting it back into an onboard storage system is appealing, and its practicality is being examined in some detail.

In the third study, we are lead laboratory in a systematic and comprehensive evaluation of storage systems for electric and hybrid vehicles. Argonne National Laboratory, Brookhaven National Laboratory, and Lawrence Berkeley Laboratory are working with us. Systems being considered include chemical, electrochemical, mechanical, and thermal storage; the performance of various classes of vehicles is also being evaluated. We expect the study to be helpful to ERDA in guiding its planning of storage systems and of electric vehicle research.

The nation's transportation problem on both the supply and end-use sides is critical. The Laboratory is assisting in assessing this problem, in planning possible solutions, and in research that can help reach those solutions.

Key Words: energy conservation, energy forecasting, transportation, transportation energy, transportation fuels.

NOTES AND REFERENCES

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3. *Urban Transportation Factbook*, Pt. 1 (Barton-Aschman Associates, Chicago, Ill., 1974).
4. For a discussion of the methanol engine as a transportation strategy for the post-petroleum era, see the December 1976 *Energy and Technology Review* (UCRL-52000-76-12), p. 6.
5. Recent progress in our *in situ* oil-shale project is described in the February 1977 *Energy and Technology Review* (UCRL-52000-77-2), p. 19.
6. Results from our first *in situ* coal gasification experiment at Hoe Creek, Wyoming, are summarized in the January 1977 *Energy and Technology Review* (UCRL-52000-77-1), p. 1.
7. Work on a flywheel-battery hybrid vehicle is described in the June 1976 *Energy and Technology Review* (UCRL-52000-76-6), p. 16.
8. Our lithium-water-air battery study is briefly described in the August 1976 *Energy and Technology Review* (UCRL-52000-76-8), p. ii.

CONSERVATION

Our Energy Future: The Case for Intensive R&D

We have used the Stanford Research Institute energy model to examine and evaluate the potential benefits to the U.S. of an intensive energy R&D program implemented over the time frame 1975 to 2025. We report here on two of the six scenarios studied: the LLL nominal case in which no additional energy R&D is undertaken, and the end-use/supply R&D case in which research and development is applied to all phases of the energy picture, from exploiting primary resources to developing new energy technologies and greater end-use efficiencies. Our results show that a vigorous energy R&D program could be of tremendous economic benefit.

As domestic supplies of oil and gas diminish, the U.S. must consider the options available for meeting

future energy demands. One option is to implement new technologies for both the production and more efficient use of energy – developing technologies that can exploit new energy sources and conserve old sources through more efficient use. This would involve various levels of research and development, at least partially supported by the government. To help evaluate this option, we have analyzed the potential benefits of implementing the results of such an intensive energy R&D program on a national scale.¹

We performed this analysis with the Stanford Research Institute (SRI) energy model² to examine different scenarios over the 50 years from 1975 to 2025. The SRI model was modified for our study to include revised data-base information and new energy technologies such as *in situ* coal and oil-shale processes for producing synthetic fuels, solar electric and electricity-storage processes, and advanced automobile engines.

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Fig. 1. The SRI energy model computes the resource supply needed for a given demand. The projected service demand and/or fuel-equivalent service demand for each year of the time frame is input to the computer. Also input is data-base information such as projected resource costs, import prices, and conversion efficiencies. Output from the model consists of energy prices and quantities (by region) for primary resources, energy-conversion products, and distributed products.

SRI ENERGY MODEL

As shown in Fig. 1, energy is generally depicted in the SRI model as flowing from primary resource to distributed product with a conversion and/or transportation efficiency factor in between. Simply stated, for 1 unit of primary resource and a conversion efficiency of 80%, we get 0.8 units of distributed product. The energy model computes the resource supply needed for a given demand. To do this (Fig. 1) we need to input to the computer,

- Service demand, which includes such numbers as the expected vehicle kilometres to be driven, the tonnes of steel to be produced, and the square metres of buildings to be heated in each year of the 50-year period.

- Conversion factors to convert these numbers into the quantity of energy needed to meet the demand, that is, the fuel equivalent (sometimes we convert from

service demand to fuel equivalent external to the computer and enter only the fuel equivalent).

- Efficiency factors and economic parameters to take into account the energy lost and costs incurred during end-use conversion processes and during primary resource conversion and transportation processes.

We must also enter the costs of primary resources and price projections for imported fuels – crude oil, methanol, Canadian gas, and liquefied natural gas (LNG). We are assuming that the country can purchase as much imported fuel as required at the specified prices.

End-use demands are divided into four major sectors: residential/commercial, industrial, nonenergy, and transportation. These major sectors are then further divided into subsectors (and separated into

eight geographical demand regions). End-use demands are the most important model input for determining the overall magnitude of energy flows.

After these end-use demands are specified, the model calculates production levels (and corresponding prices) needed to satisfy them. In a discounted-cash-flow calculation, the costs of capital, operation, and fuel are used to compute the price needed to stimulate a new increment of production for each of the competing energy alternatives. Selection of one energy alternative over another is based on price, with the lowest priced alternative capturing the bulk of the market.

Fuel cost, whether for a primary fuel like coal or a secondary fuel like electricity, is ultimately tied to the price of the primary resource, which rises as that resource is depleted. The model keeps track of the cumulative resource production and the associated costs, which form the basis of the fuel costs used in the analysis.

Output from the energy model consists of energy prices and quantities (by region) for primary resources, energy-conversion products, and distributed products for an energy supply/demand balance. Energy demand, process costs, and resource costs are fixed in each model scenario. The effect of variations in demand and costs are analyzed by using many scenarios.

SCENARIOS

To assess the potential benefits of implementing the results of successful energy R&D for the U.S., we used the SRI energy model to examine six scenarios; here we will discuss the principal two. In both scenarios R&D includes that stage of development where we have achieved an operating demonstration plant. It also includes the development of conservation techniques and practices.

LLL Nominal. In this scenario we adopted service demands corresponding to those in the "Reference Energy System," which is used in ERDA's national energy plan.^{3,4} Processes currently available or already under extensive R&D (such as surface coal gasification processes) were included, as were improvements in process efficiency presently expected to occur; the

fruits of more speculative, future R&D were not included. The price of imported crude oil was maintained roughly constant in 1975 dollars until the onset of world oil depletion; this was about \$2.50/GJ (\$2.50/10⁶ Btu) until the year 2000, then rising steadily to about \$4/GJ (\$4/Btu) in 2025. Three automobile engines were assumed to be widely available: gasoline, gasoline/methanol blend, and diesel. This scenario can be thought of as an extension of the present trend in energy policy and research.

End-Use/Supply R&D. In this scenario we assumed that improvements in end-use efficiencies and practices led to reduced fuel demands to satisfy the same service demands.⁴ Five advanced automobile designs (in addition to those in the LLL nominal case) were assumed to be widely available: a methanol internal-combustion-engine vehicle, a hydrogen internal-combustion-engine vehicle, an advanced heat-engine vehicle, a secondary-battery electric vehicle, and a primary-battery/secondary-battery electric vehicle. Also, supply technologies requiring intensive R&D were made more competitive through lower cost assumptions. These technologies included advanced surface coal gasification and coal liquefaction processes, *in situ* coal gasification, and *in situ* oil-shale processing.

LIQUID FUELS

The volumes and prices of the liquid fuels calculated for the two scenarios are shown in Fig. 2. In the LLL nominal case, imported crude oil dominates the liquid-fuel market, supplying approximately 75% of the nation's liquid-fuel needs in the year 2010. Domestic crude oil production decreases due to the onset of depletion. The production processes of the synthetic fuels included in this case — surface-shale syncrude, methanol, coal residual fuel, and coal syncrude — are expensive and have only a minor impact over the scenario's time frame. The average price of liquid fuel follows that for imported crude oil.

This liquid-fuel outlook is troubling for two reasons. First, the continuing and growing reliance on imported crude oil may be undesirable both from a

Fig. 2. Liquid-fuel production and prices for the LLL nominal case (left) and the end-use/supply R&D case (right). Imported crude is the dominant liquid fuel under present-trend conditions in the LLL nominal case. In the end-use/supply R&D case, however, synthetic fuels become available at lower prices and displace crude oil imports.

security-of-supply point of view and (potentially) for our balance of payments. Second, the cumulative quantity of imported crude required for this scenario over the 1975 to 2025 time frame represents about half of the currently estimated oil reserves of the Middle East. Considering the expected growth of demand for liquid fuel by other nations, it is questionable that the U.S. will be able to obtain this much of the world's crude oil reserves.

In contrast, the liquid-fuel picture for the end-use/supply R&D case is much more optimistic. Reliance on imported crude oil is reduced significantly as more advanced, cheaper, synthetic-fuel technologies become available. In this scenario, the *in situ* shale syncrude process captures the largest share of the liquid-fuels market. At first, the price of liquid fuels follows that for imported crude oil, but then stabilizes at the price of shale syncrude from the *in situ* process.

However, it is not clear that large-scale development of an *in situ* shale industry will be allowed to take place in the small region of Colorado where the shale is located. Environmental restrictions caused by fears of boom towns, competition for available water, and concern over water and air pollution may limit the growth rate and ultimate size of the shale industry to levels below those projected in this scenario. If this does occur, we can expect additional production of syncrudes from coal, higher imported crude oil levels, and, as a result, somewhat higher prices for liquid fuels.

THE METHANE MARKET

Methane sources and prices for our two scenarios are shown in Fig. 3. In the ULL nominal case, Alaskan North Slope gas dominates domestic production beyond the year 2010. The overall decline in domestic production, however, is supplemented primarily by first-generation coal gasification processes (for both eastern and western coals) and by a small level of imported gas. The average wellhead price of methane

doubles (in constant 1975 dollars) over the next 50 years to about \$3/GJ (\$3/10⁶ Btu).

The major contribution of successful end-use/supply R&D to the methane picture is to stabilize the methane wellhead price at about \$2.40/GJ (\$2.40/10⁶ Btu). The *in situ* gasification process for thick seams of western coal captures the largest share of the market, and gas imports are reduced to zero.

BASE-LOAD POWER GENERATION

The generation of base-load electricity (the electrical output of plants that operate essentially all the time) by fuel type and the average price of base-load power are shown in Fig. 4. Eastern coal, methane, and residual fuel (a heavy fuel byproduct of petroleum refining) are displaced primarily by nuclear power and western coal. When it becomes available, the breeder reactor is the most attractive option, capturing the growth in electricity generation. The average price for base-load power at the generating plant stabilizes at about \$6/GJ (\$6/10⁶ Btu). The predominance of nuclear over coal-fired power plants is due in large part to the transportation costs of either the coal to the plant or (in the case of a minemouth generating facility) of the electricity from the plant. Such important details can be accounted for accurately only by a regionalized energy model.

The rapid growth in conventional nuclear power generation at the beginning of our time frame exceeds presently projected growth rates based on current reactor-construction schedules and orders. This discrepancy arises from the model's assumption that, prior to 1975, decisions concerning power plant construction were made strictly on an economic basis. But decisions have in the past and may in the future be swayed by other criteria, such as public opinion or new legislative requirements.

Fig. 3. Methane production and average price in the LLL nominal case (left) and in the end-use/supply R&D case (right). In the LLL nominal case, as domestic production declines because of depletion, first-generation gasification plants and imports maintain the methane supply, but the (constant-dollar) price of methane doubles. The North Slope is the dominant source of domestic natural gas after the year 2010. In the end-use/supply R&D case, advanced coal gasification processes provide methane at reduced prices.

Fig. 4. Base-load-power fuels and prices in the LLL nominal case. Nuclear fuel and western coal become the important resources for electricity generation. The "actual" line represents the anticipated level of nuclear power generation based on current reactor construction schedules and orders. The model overstates the nuclear growth rate because it assumes that "correct" economic decisions (that is, choices for nuclear power plants) were made prior to 1975. The price of power drops at first as the shift to the cheaper nuclear power takes place. (The market shares shown are distorted by a subsequently discovered coding error. The correct result would give a somewhat larger share to coal, but would not substantially change the overall national supply/demand picture.)

AUTOMOBILE FUELS

In the LLL nominal case, we assumed three automobile engines were available at mass-production prices from present-trend automobile technologies. In the end-use/supply R&D case, five additional automobile designs were included. (Their availability in the LLL nominal case was inhibited by increasing their capital costs by a factor of two over those expected to prevail under mass production.) The fuels supplied to the automobile transportation market for both scenarios are shown in Fig. 5.

In the LLL nominal case, petroleum-based fuels continue to dominate the market. But when all eight automobile designs are available at mass-production prices, fuels for the automobile market change considerably. Gasoline and diesel use is reduced, while electricity, hydrogen, and methanol make significant market gains. In addition, the overall efficiency of the transportation sector increases, as indicated by the reduced total fuel requirement. We conclude, therefore, that when the economic factors we used to

Fig. 5. Petroleum-based fuels dominate automobile transportation under the present-trend assumption in the LLL nominal case (left). Gasoline, gasoline/methanol blend, and diesel are the three engines considered here. In the end-use/supply R&D case (right), five additional automobile technologies are considered: a methanol internal-combustion-engine vehicle, a hydrogen internal-combustion-engine vehicle, an advanced heat-engine vehicle, a secondary-battery electric vehicle, and a primary-battery/secondary-battery electric vehicle. With these new technologies available at competitive prices, alternative fuels, (electricity, methanol, and hydrogen) have substantial impact. Also, overall fuel needs are greatly reduced because of the higher efficiencies of the new automobiles.

describe the different designs are used, new vehicles can capture a significant share of the transportation market and the demand for petroleum-based fuels can be substantially reduced.

STUDY CONCLUSIONS

There are many ways to measure the potential benefits to the nation of implementing the results of

Fig. 6. Crude oil import volumes are sharply reduced in the end-use/supply R&D case. The curves peak where synthetic liquid fuels become competitive with imports. Also, large savings in import costs are achieved with the reduced import volumes.

Fig. 7. The total cost of distributed energy products to end-use markets is sharply reduced in the end-use/supply R&D case.

a successful energy R&D program. Three important yardsticks that we have considered are the program's effect on U.S. imports of crude oil, the cost of imported crude oil, and the total energy costs to the country (the cost of distributed energy products delivered to end-use markets).

As shown in Fig. 6, the effect of intensive end-use/supply R&D is to reduce crude-oil imports by 3 million cubic metres per day (18×10^6 bbl/d) in the year 2010. The annual imported-oil bill for this case rises from \$30 billion now to about \$50 billion in the year 2010; for the LLL nominal case, this bill could be \$100 billion more.

The total energy costs for both scenarios are shown in Fig. 7. The difference between the two is the reduced energy costs to the country resulting from successful end-use/supply R&D programs.

To determine the total value of the reduction in annual energy costs over the 50-year time span, we used a net-present-value calculation and several rates of return ranging from 0 to 10%. We then computed the energy-cost savings. The net present value of the

savings is enormous — \$455 billion at a 10% rate of return for the end-use/supply R&D case. However, it should be noted that this calculated value is overstated for two reasons.

First, the costs of implementing the improved end-use efficiencies and conservation efforts are not included. Nonetheless, while these costs are certainly significant, in our judgment, the conclusion that successful R&D could have a very large economic benefit is still valid.

Second, the cost of the R&D programs themselves is not included. We did make a very rough projection of an assumed ERDA energy R&D program, including \$2 billion per year for research and development and phased outlays for demonstration plants. The total investment (undiscounted) for this 50-year program is \$128 billion, and the net present cost is only \$60 billion (at a 5% rate of return) or \$38 billion (at a 10% rate of return) — small costs compared to the benefits accrued from implementing the results of a successful program.

Based on this study of an energy R&D option, we have reached the following conclusions:

- Implementation of the results of successful R&D programs can have extremely large economic benefits for the nation.

- Synthetic-fuel production can reduce U.S. dependence on imported oil from 4 million cubic metres per day (25×10^6 bbl/d) to 1 million cubic metres per day (7×10^6 bbl/d) in the year 2010 and can stabilize energy costs at \$94/m³ (\$15/bbl) for liquids and 8.5¢/m³ (\$2.40/mcf) for gas.

- Based on economic considerations alone, new fuels and engines optimized for these fuels can penetrate the automotive market.

CONSUMER PERCEPTION OF R&D

In terms of how consumers perceive the value of R&D, we believe that they are concerned primarily with three aspects of the energy situation: supply security, energy price, and environmental impact.

Embargo-caused shortages strengthened worries over relying on imports and had a strong impact on developing an awareness of the need for a national

energy R&D program. With successful R&D, supply security can be improved by developing synthetic-fuel industries to produce liquid fuels and gases from shale and coal. Also, more efficient energy end uses (improved highway vehicles, especially) can reduce the overall need for petroleum fuels.

Recent price increases in all forms of energy have caused considerable consumer apprehension about the future of energy prices. With successful R&D, synthetic liquid fuels and gases can stabilize prices. By reducing the overall demand for fuels, successful end-use R&D can also help control energy prices.

Consumers remain concerned about air pollution problems, particularly those due to the automobile. In addition, they are troubled by potential local impacts of energy plants. This was demonstrated recently in California with the nuclear power plant initiative, and it is reasonable to expect that similar concerns will develop over large-scale coal and shale production. Such concerns may revolve around safety issues, the problems of boom towns, competition for water usage, and increased water and air pollution. With successful R&D, new automobile designs could significantly reduce air pollution. Also, the *in situ* processes for synthetic fuel production may damage the environment less than surface production techniques.

Thus it appears that a vigorous energy R&D program addressing these issues of national concern should meet with public approval and, if successful, would be of tremendous economic benefit.

A Potential Problem. It was the oil embargo and sharp price increases that stimulated action on energy R&D. Increased oil production from non-OPEC sources may cause a temporary reduction of world oil prices in the 1980's.⁵ This, in turn, could cause the consumer to think — quite incorrectly — that there is no immediate need to continue a high level of energy R&D. But we must remember that the apparent world oil glut will only be temporary, that the advisability of relying on foreign oil is questionable, that energy R&D through the demonstration-plant phase is a lengthy process and therefore must be pursued without delay, and that energy R&D can reduce energy needs and costs.

CURRENT ACTIVITIES

This study convinced us of the value of energy modeling in planning and assessment activities, and that the SRI energy model has unique features making it particularly useful for energy analyses. We are, therefore, developing a model based on the same economic principles but with significant changes intended to make it more suited to our purposes. These changes include the addition of regulation models, including price controls and quantity limitations; models of pollution monitoring, taxing, and/or regulation; improved economic and financial models; and techniques to promote more efficient and convenient use of the entire energy model.

We hope to be running test problems this summer.

Key Words: energy models, energy conservation, energy forecasting.

NOTES AND REFERENCES

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ADVANCED ENERGY SYSTEMS

Direct Energy Conversion for Fusion Reactors

Almost all of the energy released in a fusion reactor will be carried by high-speed particles: neutrons, helium ions, and escaping fuel ions. The neutrons simply leave the reaction zone; most of their energy is recoverable only as heat in a surrounding blanket. The ions, on the other hand, can be manipulated because they have electrical charge. Direct converters can convert the kinetic energy of those ions that escape from the reaction into useful electrical power. In addition, the efficiency of neutral-beam injectors can be nearly doubled with direct converters to recover energy from the unneutralized ions.

The design of direct energy converters is well advanced. We have tested complex multistage plasma

converters at efficiencies approaching 90% at low energies and powers, and simpler, more cost-effective versions at 65% efficiency. Laboratory tests of neutral-beam direct converters at 15 keV and 2 kW gave 70% efficiency. We have built and are preparing to test a 120-keV, 1.5-MW version.

In a mirror fusion reactor, a hot plasma is confined by specially shaped magnetic fields and maintained by injecting beams of energetic neutral particles (see box on p. 22). Most of the energy of the fusion reactions within this plasma appear as the kinetic energy of neutrons and positive ions. The neutron energy will be captured as heat in a surrounding blanket and converted to electric power by conventional means. The positive ions from the fusion process, and from

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FUSION REACTORS: THE SUN IN A BOTTLE

The first fusion reactor will probably burn hydrogen isotopes: deuterium and tritium. Since fusion reactions take place only at extremely high temperatures (millions of degrees), the deuterium-tritium gas mixture must be kept from touching anything solid until after it has had a chance to react. (Touching the walls would cool the gas below the reaction temperature.) Hence a means of confinement (keeping the gas away from all walls) is basic to any fusion reactor.

There are three main forms of confinement: gravitational, inertial, and magnetic. The sun is a fusion reactor operating on gravitational confinement. Needless to say, man-made fusion reactors will be either inertial or magnetic.

Inertial fusion devices depend on speed. The thermonuclear burn takes place suddenly, before the hot gas can escape. The hydrogen bomb is one example of inertial confinement. Laser fusion, which plans to use extremely brief and powerful laser light pulses to ignite tiny pellets of frozen deuterium and tritium, is another.

Magnetic fusion devices confine charged gas atoms (ions) with powerful magnetic fields. Since we are unable to make a perfectly confining magnetic field, ion leakage is a problem. Although this leakage can be compensated for by pumping in energetic neutral particles with neutral-beam injectors, keeping the reaction running, a large fraction of the reactor's power output is tied up in leakage ions. In addition, the neutral-beam injectors produce both neutral atoms and ions. These ions never enter the reactor since the magnetic fields that confine the fusion plasma turn them back. Thus a scheme for recovering the energy of both leakage and injector ions is essential.

Direct converters are one means of producing electrical energy from these ions. For a summary of recent work at LLL on direct energy conversion, see the accompanying article.

the plasma itself, eventually escape past the mirrors and their energy must also be recovered. We have been working on a number of direct electrical conversion schemes for recovering this energy. These schemes can also be used to increase the efficiency of the neutral-beam injectors that sustain the plasma.

In a direct converter, fast ions expend their kinetic energy against an electrostatic gradient, finally depositing their charge on an electrode at high potential. This deposited charge is the source of power that is taken off into an external circuit. The power levels involved are quite impressive. Our proposed mirror fusion test facility,¹ still far from a full-fledged reactor, is expected to have ion currents in the 750-A range at 80 keV. An operating reactor could have currents of thousands of amperes at hundreds of kilovolts.

A complication in collecting energy from these positive ions is that they are always accompanied by electrons. That is, the overall plasma is electrically neutral. If the electrons accompany the ions to the collecting electrodes, they would cancel the positive ions and reduce the collected current to nearly zero.

The electrons must therefore be separated out with a negative electrostatic gradient. The ions, being heavy and positively charged, continue past the negative electrode to the collector electrode. The electrons stop in a grounded grid, where they are conducted externally to complete the circuit with the ions at the collector electrode.

TECHNOLOGY

These concepts are easy to describe theoretically. Many practical difficulties, however, arise in the actual design, construction, and operation of such a scheme. These difficulties may be grouped under the headings of space-charge effects, heat removal, electrode materials, voltage holding, chemical compatibility, and insulator design. We will discuss these effects briefly before going on to describe our successful experimental direct energy converters.

Space-Charge Effects. Space-charge effects take place when you have a large number of charged particles in a small volume. In a plasma, with equal

numbers of electrons and positive ions, the space charge is zero. When we separate out some of the electrons, the excess positive charge of the ions strongly attracts the remaining electrons, in effect shielding them from the separating field. It takes an excess negative potential on the first electrode to overcome this space-charge attraction and extract the rest of the electrons. In the absence of electrons, the ions' mutual repulsions disperse the beam, spreading it over a large area of the collector electrode. Space charge cannot be eliminated; it is simply a factor that must be controlled.

Heat Removal. When a positive ion hits the collecting electrode, its kinetic energy turns directly into heat. This is one of the reasons for collecting the positive ions on a positive electrode, to minimize their net kinetic energy and hence the heat they generate when striking. If the electrode potential could exactly match the ion's initial energy, no heat would be generated and hence no heat removal problem. However, since no two ions have exactly the same kinetic energy, it would take an enormous number of collection stages to fulfill this condition. We have tested experimental converters with as many as 22 stages and measured efficiencies of 90%. Simpler converters with only a few stages may be more cost effective, however.

If any large part of the ion beam were to concentrate on a small part of the collector, it could easily overheat and destroy that part. To avoid this we spread the beam out by expanding the magnetic flux tube that guides the ions. The bigger the beam current, however, the bigger the collecting electrodes must be. Designs to cope with this power density problem would be huge; a typical one would be housed in a domed vacuum chamber 100 m tall and 125 m in diameter.

Apart from heat generation, we still have the problem of removing heat from the electrodes. Each electrode must be electrically isolated, and this generally means thermal isolation as well. In the absence of other cooling, an electrode will keep getting hotter until its radiant output equals its energy input. Figure 1 shows an experimental direct converter made of molybdenum and operating with radiative cooling.

Sometimes radiative cooling is not enough, however. For one thing, at high temperatures an electrode will begin to emit thermionic electrons. These electrons could then flow to a collecting electrode, neutralizing part of the ion current. To avoid this we can circulate helium through channels in the electrodes for convective cooling. The helium coolant then becomes a secondary source of energy. For efficient thermal energy recovery from this source, we must keep the coolant temperature as high as possible, about 1000 K.

Convective cooling at such high temperatures and hence high pressures is complicated by the need to operate the various electrodes at different high voltages. Either we must design special heat exchangers to stand off high voltage, or choose insulators designed to confine high pressures at high temperatures. We are investigating various alternatives.

Electrode Materials. Anything that is to be cooled by radiation only must be made to stand high temperatures (up to 1800 K). For electrodes this means a refractory metal or carbon. Carbon electrodes have many desirable features, but they pose a problem: carbon atoms sputtered off from them could attack nearby hot refractory metals, making them brittle.

Electrodes designed for convective cooling must also have high tensile strength to withstand internal pressure and thermal stress in thin sections. Tantalum alloy (10% tungsten) has been chosen as a superior material under similar conditions in the first wall of the fusion engineering research facility design.

Voltage Holding. It seems that nature abhors a difference of potential, and the design of high-voltage electrodes must take this into account. Metal surfaces can have no sharp corners but must be smoothly rounded and highly polished. Insulators must be clean and properly shaped to provide long leakage paths on their surfaces.

When an electrostatic converter goes into operation, however, ion bombardment will immediately begin to modify these carefully controlled conditions. Insulators get dirty and start to carry leakage currents. Polished metal surfaces become rough and pitted. Practical designs must either modify or prevent these processes.

Fig. 1. Two views of an experimental direct converter scavenging ions from a neutral beam. The converter first strips away electrons, making the ions diverge out of the beam by their own mutual repulsion, and forcing them to expend most of their kinetic energy against a positive potential gradient. The upper picture shows the converter in operation, the lower shows it dismantled and turned upside down for inspection.

One effect of He^{++} ion bombardment on metals is surface blistering. The ions' kinetic energy drives them below the surface of the metal where they accumulate, weakening the crystal lattice and eventually building up internal pressures that raise blisters. Operating the electrodes at high temperatures helps prevent blistering by increasing the ion mobility and letting the helium escape from the surface instead of accumulating.

Another effect of ion bombardment is sputtering, a process that blasts atoms loose from a conducting surface and sends them zinging off through the surrounding vacuum. This is more of a long-term problem; it takes time to remove enough material, atom by atom, to seriously affect a metal surface. Still, the rates are not negligible. We estimate that tungsten wires will erode at about $20 \mu\text{m/yr}$, and carbon fibers would go even faster.

The other half of the sputtering problem is what happens to the blasted-off atoms. They have to go somewhere, and many go where they are least welcome. Little by little they build up a conducting coating on insulator surfaces.

We have been coping with such problems for years and have a number of ways of shielding the insulators to slow down the sputtered-film buildup. No shielding system yet devised is 100% effective, however. Sooner or later the insulators will have to be replaced. One aim of any practical design will be to make the replacement interval as long as possible.

Chemical Compatibility. One of the materials we might make electrodes of is graphite; it's cheap, available, and heat resistant. Chemically, however, it may be a problem. Hydrogen ions attack carbon directly, forming volatile methane and eroding the surface. Graphite also has a known tendency to adsorb hydrogen, e.g., tritium, although we cannot be sure how much of a problem this will be because we lack experimental data.

Another potential problem is carbiding, the reaction of carbon with metals at high temperatures. For example, one concept that called for graphite platelets strung on tensioned tungsten wires is being reexamined because it developed that the wires would quickly convert to brittle tungsten carbide. To avoid carbiding,

we could either eliminate graphite electrodes, or keep all metal parts below about 1000 K.

Insulator Design. Insulators used in direct converters will have to be carefully designed to stand up to a harsh environment. They will be bombarded with neutrons, charged particles, and gamma rays. Above a certain level, gamma rays can turn an insulator into a semiconductor, causing catastrophic failure. Both neutrons and charged particles can damage the insulator surface by sputtering, and the neutrons can also damage the insulator internally by inducing nuclear reactions. The insulators will also require special cooling to protect them from high temperatures.

EXPERIMENTAL DIRECT CONVERTERS

Most of the above ideas, although developed in connection with direct energy conversion, also have present applications to improving the efficiency of neutral-beam injectors. Much of our recent success in mirror fusion experiments involves the use of neutral beams, and the efficiency of neutral-beam injectors could have a large bearing on the overall efficiency of a fusion power plant.

Our neutral-beam sources operate by generating an intense beam of hydrogen ions, accelerating them to a high velocity, and adding electrons in a gas cell to convert the ions back to neutral atoms. The first two steps are reasonably straightforward; in the third step, serious inefficiencies crop up. Our methods for neutralizing ions in flight are strictly statistical; at the energies required in reactors, the emerging beam still contains about 60% unneutralized ions. These carry a corresponding fraction of the total beam energy, energy that would be wasted unless converted back into electrical energy.

Figure 1 gives two views of an experimental beam-ion energy converter under test in a vacuum chamber and turned upside down for easy access during assembly. The checkered effect in the ion beam and on the various lighted surfaces in the upper picture is the result of photographing the electrodes through a grounded wire mesh cage placed around the

Fig. 2. A scaled-up direct converter being built to handle 120-keV H^+ or D^+ ions. The elliptical cross section follows the density contour of the beam. The first aperture, with adjustable tungsten plates to define the beam's boundary, is 39 cm tall and 9 cm wide. In operation the sharp corners and rough surfaces will be covered with smooth shrouds to avoid voltage breakdowns.

apparatus to maintain electrostatic shielding without blocking removal of the resulting gas. The rows of red and green lights in the upper right corner are not in the vacuum system but are reflections in the viewing window.

Some of the construction features are easier to see in the benchtop view. Note the antispattering shield around each high-voltage insulator. Also note the cleaned area on the copper beam stopper (extreme right in lower picture, no longer on axis) where neutral atoms and ions that escape collection have sputtered away the brownish surface film.

This experimental energy converter was operated in front of a steady-state ion source masked to produce a slab-shaped beam 15 mm thick and 60 mm wide consisting mostly of H^+ ions. We varied the ion energy from 10 to 15 keV. This in turn varied the full-energy ion current from 50 to 130 mA. When the photograph was taken, the device was recovering 1 kW of electrical power and rejecting less than half that much as heat. This represents optimum operation, with about 70% efficiency.

Figure 2 shows a scaled-up version (under construction) of the same kind of direct converter, designed to handle 120-keV H^+ ions. When completed it will be used to recover 1.5 MW (13 A at 120 keV) of ions from a neutral-beam source at the Lawrence Berkeley Laboratory. Radiation cooling would not be enough for a converter this size, so the electrodes are all of water-cooled copper, nickel plated to reduce sputtering. In operation the supports and rough exterior wall will be covered with smooth shrouds to avoid voltage breakdown.

The Berkeley source has a square output aperture 10 cm on a side. Where the converter will be, 5 m away, the beam profile is Gaussian with an elliptical cross section, however. Hence all the electrodes and apertures in the converter also have elliptical cross sections. The first aperture is the smallest, with major and minor diameters of 36 and 9 cm, respectively. At maximum power and best focus, the beam power density striking this first aperture (around the fringes of the beam) will be 0.5 kW/cm². Total power density (neutrals plus ions) at the center of the beam will be 37 kW/cm².

In anticipation of favorable results from these tests, we are developing preliminary designs for a direct converter to couple with the injectors for the tokamak fusion test reactor at the Princeton Plasma Physics Laboratory. We assume that the injectors will be elongated 10- X 40-cm versions of the 10-cm square source being developed at Berkeley. There is no room to spare in the test reactor design, however, so the converter must operate close to the source. At this distance there will be no convenient Gaussian distribution; the 4-MW beam of unneutralized ions will have nearly a flat-topped profile and will be the full 10 cm thick. The space-charge potential at the center of such a beam (with the electrons removed) is enormous. It would take about 80 kV on the negative electrode to turn back the electrons.

Such a high negative potential is impractical because of power losses and the danger of sparking. One possible solution is to chop the beam height to 5 cm, reducing the required negative potential to about 20 kV. Unfortunately, this would halve the beam output, making it necessary to double the number of beams.

A better way to do this may be to modify the ion source to cast a shadow down the center of the beam. We could then add a web down the center of the negative electrode, in effect dividing the former beam into two beams of half thickness. This would reduce the negative potential to 20 kV without requiring additional sources. We are studying other concepts, such as transverse magnetic fields, for controlling electron flow in the beam.

Figure 3 is an artist's conception of such an ion source-converter combination. Flat panels arranged like louvers and equipped with coolant-circulation channels serve as collector electrodes. A pair of curved electrodes at the entrance of the converter trap fractional-energy ions that carry little of the beam energy, but would represent a serious heat load on the cryogenic pumping panels if they were not stopped.

A converter to improve the efficiency of a neutral-beam injector has one big advantage over a converter intended for the output end of a fusion reactor: it deals with a well-defined beam of more-or-less monoenergetic ions. A plasma direct

Fig. 3. Conceptual design of an ion source-converter combination for a 120-keV neutral-beam source. The ion source, left, generates a sub-beam of 120-keV deuterium ions. In the neutralizer cell, about 40% of the ions turn back into atoms, still at 120 keV. The converter traps the remaining ions, converting most of their energy into electricity to help run the ion source. The 120-keV deuterium atom beam passes unimpeded into the reactor.

converter, on the other hand, must separate the electrons from a diffuse (though directed) flow of ions of widely varying energies, sort the ions according to energy, and collect the energy from each segment of the ion population. Most of the concepts described for beam converters are still valid in this application, but the apparatus embodying them is extensively modified.

Figure 4 shows a triple-stage (Venetian blind) direct converter designed to handle ions with a mean energy of 178 keV and a minimum energy of 100 keV. Wire grids replace the grounded aperture and negative electrode. Flat fins, arrayed like louvers set in planes almost at right angles to the incoming ion beam, form a series of three collector electrodes of increasing potentials. Energetic ions pass through the louvers until

they expend their kinetic energy, then they fall back in parabolic trajectories onto the next lower collector. Since the ions are collected on the backs of the intermediate louvers, we can suppress secondary electrons by locating a slightly less positive grid behind each intermediate collector. We calculate that such a converter should have an efficiency of 60% after allowing for the 8% of the incident power carried by electrons.

Since the average power flux into this converter is only 0.5 to 1 MW/m², we can make the grounded grid, the negative grid, the two intermediate collectors, and their suppressor grids all of carbon fibers cooled only by radiation. The surrounding walls and the third collector are convection cooled with 1000-K helium

to scavenge the excess ion energy and radiated heat. The support posts are water cooled to protect the high-voltage insulators.

The fins of the final collector, at 250 kV, are folded into a chevron pattern. This blocks off all line-of-sight paths through the collector, assuring that every ion that penetrates this far will stop here. Neutral gas molecules can still bounce through, however. The entire structure is as light and open as possible, providing a good pumping path for removing stray gas from the spaces between the various high-voltage louvers and grids. The pressure here and in the expander must be kept below $1 \mu\text{Pa}$ to avoid charge-exchange losses.

More intermediate collectors could be added to this design, but little is gained. The collection efficiency of each additional stage decreases rapidly and is soon offset by the increasing proportion of the incoming beam that is blocked off by the extra louver sets.

We have experimentally tested a two-stage version of this Venetian blind direct converter, first with an ion source and later with a plasma source and magnetic expander. The measured efficiency was in good agreement with the calculated efficiency (65% measured vs 69% calculated).

We have also studied two different slab-geometry direct converters. Both depend on a magnetic expander to form the plasma stream into a slab of well-directed ions. The magnetic field swerves abruptly at the entrance to the converter. Electrons are light and easily swayed. They turn aside, while the energetic ions cross the field lines and enter the direct converter.

The simplest slab converter is the space-charge-dominated, four-stage device shown in Fig. 5. It is similar to the beam direct converter shown in Fig. 3. The first electrode is an electron repeller to stop any electrons that get past the magnetic diversion. Robbed of the neutralizing influence of the electrons, the ions repel each other and the beam diverges. Low-energy ions diverge fastest, so they are the ones most likely to strike the first positive electrode. Each succeeding electrode pair is at a higher positive voltage, maintaining an electrostatic gradient that also helps sort the ions according to energy. Voltages V_1 , V_2 , V_3 , and V_4 are adjusted, according

Fig. 4. A three-stage Venetian blind direct converter module designed to handle ions leaking out of a fusion reactor. The beam passes first through an expander that spreads it over a large number of similar converters. The converter must accept ions over a range of energies coming in a diffuse (through directed) flow rather than in a well-defined beam. Thin wire grids replace the ground plane aperture and negative electrode. A series of collection electrodes accommodates the ion energy range. Ions, except for the most energetic ones and those few that hit the louvers directly, pass through until they expend their forward momentum, then turn in a parabolic arc and fall back on the next lower collection louver.

Fig. 5. A four-stage, space-charge-dominated, slab converter for a fusion-reactor output. A magnetic expander (not shown in detail) spreads the beam into a fan-shaped slab. A kink in the directing magnetic field siphons off most of the electrons, only slightly perturbing the ion trajectories. A negative electrode turns back the remaining electrons. Space charge then blows up the ion beam, spreading it over the collecting electrodes. Voltages on the different collecting stages would be adjusted for optimum power output, depending on the ion energy distribution.

to the ion energy distribution, to maximize the power recovered.

The other slab converter we have studied was based on periodic electrostatic focusing. Its 22 stages gave it a high efficiency even with a broad ion-energy distribution. However, its sensitivity to space charge makes this direct converter large and hence costly.

COSTS

Just which plasma direct converter is finally picked will depend on a cost/benefit analysis. For a fusion power reactor, the governing parameter will probably be the total cost per unit of net electrical power output. Other considerations such as the effect of waste heat on the environment, however, may dictate a high-efficiency design even at increased cost.

The direct converter will provide about half of the gross electrical output of a D-T-fueled mirror reactor, and even more for an advanced-fuel reactor. For these reactors, therefore, the efficiency of the direct converter has a strong effect on the net electrical

output. Even a slight efficiency advantage may be enough to make an expensive direct converter competitive.

In D-T-fueled tokamaks and fusion-fission hybrid reactors, on the other hand, leakage ions carry only a small fraction of the total power. The choice of a direct converter for such a reactor would therefore be dictated by other considerations, such as magnetic field geometry and pumping requirements.

Key Words: direct energy conversion; direct energy conversion -- Venetian blind; fusion-fission reactor; high temperature materials; mirror machines; neutral beams; plasmas; space charge; thermonuclear power generation; tokamaks.

NOTES AND REFERENCES

1. The LLL magnetic fusion energy program in general and the mirror fusion test facility in particular (then called MX) are described in the June 1976 *Energy and Technology Review* (UCRL-52000-76-6), pp. 1-15.

ENVIRONMENT AND SAFETY

Fire-Effluent Characterization and Containment Experiments

A major concern when fire occurs at a nuclear facility is containment of the fire effluent, a necessary measure to prevent the dispersal of radioactivity. To overcome the most serious problem – that of fire effluent plugging the filtering system – we need a more exact understanding of the character of smoke particle size distribution and particulate concentration.

Contact James R. Gaskill (Ext. 3868) for further information on this article.

For this purpose we have constructed a full-scale fire test facility at LLL, and have run an initial series of experiments.

Fire in laboratories or facilities where radioactive materials are used creates a special problem. As with an ordinary fire, it must be extinguished. But unlike an ordinary fire, the fire effluent must also be contained to prevent the dispersal of radioactivity that can pose a hazard both to those immediately involved in the fire and to the general public. For this reason, considerable care is taken not only to prevent fire in

these facilities, but also to suppress it quickly and to mitigate its effects should it occur. This requires rigorous fire-prevention and emergency procedures as well as careful design of the facilities and selection of the materials used in them.

Several means are employed to confine the radioactive materials in facilities where radioisotopes are used, stored, or processed. These procedures and structures are not designed specifically to control fire-related radioactivity dispersals, but, rather, they have been instituted to prevent dispersals from any and all mischance or unforeseen hazard. They include:

- **Negative pressure.** Radioactive materials are placed in enclosures that have a lower pressure than the surrounding workroom; the workroom is maintained at a lower pressure than other areas in the building, and the building itself is kept at a lower pressure than the outside atmosphere. This descending order of pressure from the outside in assures that all air leaks will be directed inward from clean areas to areas containing radioactive substances.

- **Collection devices.** Work areas are equipped with collection systems such as scrubbers and absorbers to prevent the escape of mists or acid vapors liberated by chemical reactions.

- **Filtration devices.** Exhaust ventilation from the work areas passes through high-efficiency particulate air (HEPA) filters installed in the ductwork. These filters, composed of pleated fibrous glass mats sealed into frames with elastomeric adhesives, can trap particles as small as $0.3\ \mu\text{m}$ with an efficiency of 99.98%.

When a fire occurs in such a facility, the essential concern is to maintain the work areas at a pressure lower than that outside to prevent the dispersal of radioactive material. Two problems arise, both resulting from the fact that air must continually be withdrawn through the HEPA filters to maintain the inner negative pressure. First, the integrity of these filters may be impaired by hot gases that attack and weaken the elastomeric sealer. Smoke and any contained radioactive matter can then be released. Second, the filter may be clogged by smoke particulate matter. Exhaust ventilation will then lessen, and

pressure in the room where the fire started may become higher; this can lead to the spread of heat, smoke, and contamination throughout, and possibly outside, the building.

We developed a countermeasure to the problem of hot gases weakening the elastomeric sealer several years ago by simply using water sprays in the ventilation ductwork to cool the gases before they reached the filters.¹ This protected the elastomeric adhesive. Later work attempting to simulate the production of smoke particulates of various materials used in laboratories proved unsuccessful because we were unable to duplicate the materials' "real life burning rates." We did find out, though, that when small amounts of these materials were pyrolyzed or burned, the filters plugged up readily.²

Later tests with simulated fuel loadings in a Quonset hut confirmed this fact, but also indicated that the problem could not be properly addressed without resorting to full-scale compartment (that is, laboratory room) tests. We therefore constructed and equipped a full-scale fire test facility and have been using it to analyze filter plugging and to develop appropriate countermeasures.³

FIRE TEST FACILITY

The full-scale fire test facility consists of several elements (Fig. 1). These include:

- A 100-m^3 fire test cell (5.9 m long by 4.0 m wide by 4.2 m high) and an associated control room containing view ports, gas sampling and analytical equipment, controls for a sprinkler system, and a CRT display capable of showing the constantly updated data obtained from sensors located in the test system.
- High and low exhaust ducts leading through dampers to the experimental duct system.
- A bypass air pollution control system used to clear away the fire effluent after a test.
- A pit for waste water collection and monitoring.
- A computerized data acquisition system.

The fire test cell is insulated internally with 138 mm of a sprayed-on alumina-silica mixture capable of withstanding internal temperatures in excess of 1000°C . To guard against slippage resulting from

Fig. 1. LLL's fire test facility. The test cell and attached control room are in the right half of the picture. High and low exhaust ducts exit from the left of the test room, join, and lead into experimental ductwork or to the scrubber system. The waste water collection pit is below ground in the chained off area and collects separately waste water from the scrubber system and from the test room. The data acquisition and reduction room is out of the view to the right.

differential expansion during heating, the insulation is held in place with 1400 stainless-steel fork, welded onto the interior skin of the cell.

Temperature and pressure sensors are located in the ductwork. Thermocouple temperature sensors are located in the test cell, which also contains optical-density, pressure, and radiant-heat flux sensors.

PREPARATIONS FOR EXPERIMENTS

To prepare for our experimental work we obtained photographs and listings of various laboratory furnishings from ERDA contractors throughout the country. We tabulated this information as fuel-load concentrations, that is, kilograms of combustible fuel per unit floor area (kg/m^2). We also classified the materials as "dirty" or "clean" burners based on our past experience and that of others in the field. A dirty burner is defined as a fuel that, in a well-ventilated fire, will produce a large quantity of smoke particulate matter; a clean burner is the opposite. We then plotted the dirty-to-clean (D/C) weight ratio of these furnishing materials against the fuel loadings for the various laboratories. From the distribution obtained we made mathematical analyses of the concentrations of the various points and arrived at smoke-and-fuel loadings, which we believe represent extreme cases. These are, respectively, D/C ratios of 5 and 0.5, and combustible loadings of 5 and 20 kg/m^2 .

We then obtained surplus laboratory furnishings from various ERDA contractors and designed furnishing systems typical of those used in ERDA laboratories and consistent with the parameters decided on. Finally, we performed the experiments.

The experimental program was divided into two phases: (1) an evaluation of the heat and smoke concentrations delivered to the H&PA filter by various likely fire scenarios, and (2) the development and evaluation of countermeasures. The fire scenarios have been divided into three experiment sets to examine the effects of various fuel and smoke loadings, the effects of high vs low exhaust ducting, and the effects of the use vs nonuse of automatic sprinklers in the test cell.

INITIAL EXPERIMENTS

Our first experiment (Fig. 2) was conducted to evaluate the operational characteristics of the test system and to determine the filter-plugging effects of a dirty (D/C = 2.7), moderately heavy fuel load (10 kg/m^2) using the high exhaust duct. The fire was lit by igniting 2 litres of isopropyl alcohol in pans located under the test fuel. After the initial flaming, the fire tended to overpressurize the cell and produced large quantities of dense smoke. The filter was plugged in less than 10 min. We extinguished the fire at 13 min, and examined the fuel remaining. About 40% of the clean items, but only one-quarter of the dirty items, had been pyrolyzed or burned. Total fuel loss was 30%.

A second test with laboratory furnishings of the same fuel concentration but of a clean variety (D/C = 0.6) showed that when the one dirty item (a plastic hood) ignited, the fire became dirty and the same room-overpressurizing phenomenon occurred as noted in the first experiment. Attempts to depressurize the room by increasing the exhaust ventilation resulted in more rapid filter plugging than in the first case.

In both tests the smoke particulate concentration in the exhaust ductwork was heavy: 3 to 4 g/m^3 of effluent.

As a result of several other experiments with either different furnishing arrangements or diesel fuel floated in a pan of water, we concluded that better information could be obtained by igniting crisscrossed piles (cribs) of identical materials to characterize smoke production (particulate concentration and particle size distribution) and filter-plugging effects. The crib configuration was chosen because this has been used as a standard test fire for various experiments in this country and also because wood-crib fires have been fairly well characterized.

To maintain the fuel within the flame zone when testing plastic cribs, we had to construct the fuel pile by inserting the rectangular plastic pieces through the openings in a cubical metal cage in a crosspled configuration. We also applied this technique to certain wood cribs to maintain the same ventilation space within the pile for correction purposes.

Fig. 2. First experiment in the fire test facility. (top) Set-up of simulated laboratory furnishings before the test. The fuel load was 10 kg/m^2 (237 kg total) with a dirty-to-clean ratio of 2.7. (left) After 30 s of burn. (right) After 60 s of burn. (bottom) At completion of burn. The filter plugged in less than 10 s and the fire was extinguished at 13 min. The fuel loss was 69 kg.

Because large fuel cribs (100 to 150 kg) are not readily ignited or kept burning, we used a gas burner under the pile both to ignite the fuel and to force its pyrolysis or combustion throughout each of these tests.

The results of several tests with cribs of Douglas fir and of a clear plastic used in glove-box windows are summarized in Table 1. From these tests we have observed the following:

- An initially well-ventilated, uncaged, wood-crib fire burns rather cleanly, produces a light smoke containing a small tar-to-carbon ratio, and does not plug the filter readily.

- A moderately ventilated, uncaged, wood-crib fire burns well initially, but soon becomes starved for oxygen and changes to a pyrolytic mode, that is, the smoke particulates show a high tar-to-carbon ratio. This kind of smoke tends to readily plug filters.

- A caged wood-crib fire, moderately ventilated, changes to the pyrolytic mode even sooner and plugs the filter in a shorter time.

- The use of an automatic sprinkler system on such a caged wood crib controls but does not extinguish the fire. However, it noticeably extends filter life.

- A well-ventilated crib of a particular plastic shows similar characteristics to that of an uncaged wood crib under similar conditions.

- The moderately ventilated plastic-crib fire tends to change to a pyrolytic mode and plug the filter fairly quickly, similar to the moderately ventilated caged wood crib under similar conditions.

- The use of a sprinkler system on the moderately ventilated plastic crib does not appear to have any beneficial effect in regard to extending the filter life, although it does apparently control the fire in the cell.

We have conducted a number of experiments on smoke scrubbing using various kinds of scrubber systems with and without the addition of wetting agents to the scrubbing water. Some smoke was scrubbed out of the system. However, these techniques appear to be selective in that they do not remove the fine particulate matter that seems to be the prime agent in filter plugging.

Table 1. Fuel-loss, smoke, and filter-plugging characteristics of wood- and plastic-crib test fires.

Fuel	Initial vent, l/s	Sprinklers used	Fuel loss rate, kg/s	Particulate concentration, g/m ³	Smoke characteristics					Time to plug filter, ks
					Tar, %	Carbon, %	CO, %	O ₂ , %	CO ₂ , %	
<i>Crosspiled uncaged</i>										
Wood	500	No	0.13	1.0	<10	~90+	3	6	—	>1.0
Wood	250	No	0.10	12.0	87	13	6	4	—	0.9
<i>Crosspiled through openings in a metal cage</i>										
Wood	250	No	0.23	—	56	44	5	4	—	0.37
Wood	250	Yes	0.11	—	—	—	2	9	13	>1.0
Clear plastic ^a	500	No	0.11	1.4	—	—	0	13	3	>1.0
Clear plastic	250	No	0.03	4.0	67	~33	2.6	12	4	0.47
Clear plastic	250	Yes	0.03	—	—	—	1	19	4	0.40

^aFire retardant was a component of the plastic used in all these tests.

For the immediate future, we will continue to characterize smoke – and its filter-plugging capabilities – generated by cribs made of other materials of interest. The effectiveness of automatic sprinkler systems will be investigated at the same time. We will analyze the smoke using cryogenic sampling techniques followed by gas chromatography. With this procedure and our particulate sampling-and-analysis system, we expect to understand more fully the character of smoke and the mechanism of filter plugging. Further work can then proceed towards developing effective smoke abatement methods.

Key Words: fire fighting; nuclear safety; nuclear accidents; radiation safety; reactor safety.

NOTES AND REFERENCES

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PAST TITLES

Articles in the *Energy and Technology Review* have been organized into subject areas approximately corresponding to the Assistant Administrators' areas of responsibility in the Energy Research and Development Administration. These subject areas are listed below with references to some recent articles in each category. (A semiannual index appears in the June and December issues.)

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