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LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

DEVELOPMENT OF MATERIALS
FOR ENERGY-RELATED APPLICATIONS

J. S. KANE

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MASTER

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**DEVELOPMENT OF MATERIALS
FOR ENERGY-RELATED APPLICATIONS**

J. S. Kane

A B S T R A C T

In this paper I will discuss several areas in energy systems where materials research and development will lead to improvements in the efficiency of energy utilization. I will consider improvements in current technology as well as new technologies.

The theme of this address will be the application of materials science and technology to develop new energy sources, and to make current energy systems more efficient. Although the per capita energy requirements and details of energy use may vary in different nations, the need for new or at least improved technology is universal.

It is probably true that there is no energy "shortage" in the world, nor need there be in the future. The basic question is: "Will energy be available at a price society can afford, and can it be generated, transported and consumed with minimal impact on our common environment?"

The world today depends largely on conventional sources of energy. By this I mean almost entirely on fossil fuels, to a smaller extent on hydroelectricity, and on a small as yet, but growing, nuclear capacity. This pattern will change as the following, inevitable events take place:

1. Available hydroelectric sites will be used up.
2. Costs of fossil fuels will rise as readily available resources are consumed, and as expectations of citizens rise.
3. The capital costs of "new" energy sources will cause energy costs to rise. Environmental restrictions will raise costs from some sources more than from others.

It is obvious that we, the technologically advanced nations, must develop a strategy to develop efficient production and use of energy, and that this plan must address both short and long range questions. By short range I mean approximately the next 25 years, which is probably much sooner than any major, new technology can be introduced. The long range question

implies using one of the "inexhaustible" sources of energy: breeding nuclear fission, thermonuclear fusion, solar energy, or deep lying geothermal energy. This is not to imply that other sources will not be important, for example wind, tidal, and thermal and chemical gradients in oceans and rivers, but the latter are localized, and probably not available in sufficient quantity to make a major impact on a global scale.

Where, then, can we most fruitfully apply our materials efforts to yield the greatest short and long term benefit? In this address I will give you my opinions on this matter, realizing that on so large a question a truly comprehensive view is impossible -- especially in a half-hour talk!

The first point I will urge you to remember is that in dealing with the production, conversion and transportation of energy, we are involved with an immensely large and costly system. It is the overall system that should be optimized, and in choosing an individual component for work, we should choose only those components where improvement will yield the largest benefit for the overall system.

As an aid in presenting my talk, I will divide my subject matter into three categories, which I have defined as follows:

SOURCES: The physical or chemical process from which the energy is obtained.

CONVERSION: The process by which the original form of the energy is changed to a more useful, convenient, or transportable form. In this paper I have assumed that this change is to electricity or hydrogen gas.* There are other possibilities; these two are

* It may be surprising to some that I consider hydrogen to be an important alternate form of energy. I will discuss the reasons for this subsequently.

the most probable forms that require the least modifications in our existing distribution systems.

TRANSPORTATION: The shipment of energy from one point (usually the source) to its point of consumption, or point of further conversion.

The second classification of topics I will make is even more arbitrary. I have chosen to mention further only a limited number of areas, ignoring other equally interesting and important ones. Here are my choices:

SELECTED FOR DISCUSSION

SOURCES: Fossil fuels
Solar energy
Thermonuclear energy

CONVERSION: Thermal cycles
Solar photovoltaic
Thermal decomposition of water.
Hydrogen-air fuel cells

TRANSMISSION: Hydrogen pipelines
Superconducting or cryogenic electrical transmission lines.

NOT TO BE DISCUSSED

Fission nuclear energy
Geothermal energy
Tidal, wind, thermal gradients in ocean.

Electrical generation
Electrolysis

High voltage, AC or DC
Cryogenic liquid transportation

MATERIALS PROBLEMS

Sources

Fossil Fuels -- In fossil fuel utilization, improvements are needed for increased efficiency and in reducing pollutants, especially sulfur. Any long range approach to fossil fuels must focus on coal, since this is by far the most abundant resource. It is remarkable, however, that the way we burn coal has changed little during the last few hundred years, other than to replace the man with a shovel with a power driven machine. Novel ways are needed to convert coal to an easily transportable form (e.g. CH_4 , H_2 , liquid hydrocarbons or alcohols) and simultaneously to remove the sulfur, the most objectionable pollutant. One technique is to convert the mined coal to "power gas", a low energy content mixture of hydrogen, hydrocarbons, carbon dioxide and nitrogen. This gas, while not suitable for some uses, is completely satisfactory for efficient, advanced thermal cycles for generating electricity. Materials work is crucial in each step of this process. For instance, the conversion could utilize MHD, or more likely high temperature gas turbines as "topping" cycles whose exhaust then powers a conventional steam cycle.⁽¹⁾ Another approach is to somehow gasify the coal underground, without mining.⁽²⁾ The resulting CH_4 or hydrogen could be separated from CO_2 and distributed by pipeline, perhaps in existing systems.

Solar Energy -- I will not consider uses such as reflectors for cooking, home heating, etc., although these may become quite important.

The chief problem with solar energy is the low areal energy density. The challenge is to collect this energy and convert it to a transportable form at sufficiently low cost. No one has yet conceived a method of doing this at a capital cost anywhere near that of competitive sources, such as fission nuclear or conventional fossil fuel. It takes only a cursory consideration to

become convinced that schemes requiring arrays that track the sun, or require optical quality components are not apt to become economic in the foreseeable future. --

A much better approach is to use planar absorbers that can achieve reasonable efficiency without focusing optics. Two techniques that meet this requirement are direct conversion to electricity by means of photovoltaic cell arrays, and collection of thermal energy with subsequent conversion to electricity via thermal cycles and rotating electrical generation. Both ideas are inefficient; the photovoltaic cells because low energy photons do not contribute, and the thermal collectors because their low temperature implies a Carnot cycle of low theoretical efficiency. For both, then, it is essential that the cost per unit area of collector be made as low as possible. The thermal collection approach depends mainly on developing very inexpensive materials that will attain as high a temperature as possible. Also, if a thermal conversion cycle (probably Rankine) is used, it will doubtless be necessary to use a low-boiling fluid, such as isobutane, rather than water.

The photovoltaic arrays must also maximize efficiency against cost per unit area. Single crystal silicon cells are currently the most efficient means of direct conversion, but to interconnect cells made from individual crystals would be unfeasible for the large areas needed. What will be necessary are techniques for manufacturing cells of very large area so the number of parallel connections can be minimized. It might be possible to use vapor deposition to obtain large area, thin-film cells such as CdS. The major task is to increase the efficiency and lower the cost. It is also worth mentioning that the basic processes occurring in such cells are very poorly understood.

A problem that inevitably accompanies solar energy utilization is the need to store energy in some form during dark periods. Suggestions have been made to use thermal storage or pumped hydrostorage. Both ideas have great practical difficulties.

If hydrogen gas were to be the product of solar energy collectors, either from electrolysis of water or from thermal decomposition of water, the storage would be somewhat simpler, using the same methods currently used for storing methane. I will return to thermal decomposition of water later, since I believe this is an extremely important topic.

To couple electrolysis cells with photovoltaic arrays seems an ideal combination, since electrolysis is a low voltage, DC process. Perhaps a large, modular panel could be vapor-deposited, and connected to its individual electrolysis cell. Modular arrays have great economies in manufacture, maintenance, repair, etc.

Thermonuclear Energy -- To date, the feasibility of obtaining energy from thermonuclear reactions has not been demonstrated, although efforts are being conducted in many nations in both magnetic and inertial (laser heated) confinement. (3) Even if the scientific feasibility of either approach is demonstrated, there will be a large effort required to bring the concept to the point of economic, predictable performance. If our experience with fission reactors is any indication, (and I believe fusion reactors will be far more challenging technologically) most of the difficulties will lie in the area of materials. For illustration let me list five of the problems that must be solved before thermonuclear energy will become economic. I have assumed that the DT reaction will be used; therefore T must be "bred" by neutron capture in ${}^6\text{Li}$.

1. Corrosion problems in Li-containing "blanket".
2. Diffusion, migration and permeation of T in structure.
3. Radiation damage problems in structure.
4. Development of economic superconductors for magnetic confinement.
5. High-temperature materials for efficient thermal conversion.

As more detailed studies are made, new problems will emerge. My colleague, Professor Richard Borg, will describe one such problem that he is studying and one that I believe to be very fundamental. It is illustrative that much basic solid-state science as well as technology will be required for the development of practical, economic thermonuclear energy.

Conversion

Thermal Cycles -- I have mentioned the need for more efficient thermal conversion (liquid metal Rankine, high temperature Brayton, MHD). Without exception, current efficiencies are limited by the high temperature capabilities of materials. Work is being done, but much more is required. It is worth pointing out that rejecting waste heat is expensive, especially where environmental limitations are imposed. This is an additional incentive for increased efficiency.

Current fossil fuel conversion technology is chiefly limited to steam cycle efficiencies, about 40%. In the past, fossil fuels have been so cheap that development of more efficient cycles, which are inherently more complex and expensive, was not warranted. Also, the relatively low-temperature water cooled nuclear reactor has stifled incentive to increase conversion temperatures. This situation will change, however, as the liquid metal cooled breeder reactor is developed, since its design will push the steam cycle to

its supercritical limit. An even greater impetus toward higher temperature conversion will be the high temperature, helium cooled reactor. It would be intolerable if conversion cycles were to place a limitation on the efficiency of nuclear electrical generation. Much work on improved materials for combined cycles, novel cycles, and above all, high temperature cycles will be required.

Thermal Decomposition of Water -- It is well to remember that new sources of electricity do not solve all our energy requirements. For example, most vehicles need a fuel with greater capability than batteries can provide.

As long as fossil fuels are available, hydrocarbons will be our best portable fuel, but in the long run we will need another. Hydrogen has been proposed by several authors (4) as the most suitable. A problem of high priority, therefore, is the interconversion between heat and hydrogen. This can be achieved with present technology by first converting the heat to electricity, with a loss of perhaps 60%, then electrolyzing water, at an efficiency of perhaps 85%. This is extremely wasteful of energy.

It should be possible to decompose water into its constituents directly by heating. For a single step process, the temperature required is unacceptably high, again because no materials exist that are suitable. By using a multi-step process, in which no materials are consumed except water, it should be possible to decompose water at temperatures well within the capabilities of high temperature nuclear reactors, either fission or fusion. In fact, even lower temperatures, such as could be obtained from solar thermal panels or geothermal sources, may eventually be sufficient. Although at first the problems encountered in obtaining hydrogen from water appear to be

predominantly chemical, I have no doubt materials will play an essential role in their ultimate solution.

Electricity from Hydrogen -- One can always obtain electricity from hydrogen by combustion followed by conversion via a thermal cycle. A far more attractive alternative is the hydrogen-air fuel cell, which is not limited to Carnot cycle efficiencies. Efficient fuel cells are therefore an essential component of a hydrogen-based energy economy.

Fuel cells are already in use, and hydrogen is in many ways an ideal fuel. The theoretical efficiency is very high (83%), they are quiet, generate few pollutants, and are not hazardous.

One of the chief advantages of fuel cells is that they are modular; the cost per kilowatt capacity does not vary strongly with station size. There are advantages to dispersing the conversion in smaller units close by the consumer. Electrical line losses are reduced, and use of waste heat for space heating or cooling is possible. (5)

The materials problems in fuel cells are chiefly those of corrosion, and of devising economic but highly efficient electrode surfaces.

Transportation of Energy

In the 21st century fuel economy I foresee, energy will be transported predominantly in two ways -- via electrical transmission lines, and via pipelines containing hydrogen and perhaps hydrocarbons or alcohol. Again, both electrical and gas transportation will involve materials development.

The most dramatic improvement in electrical transmission would be the large scale development of cryogenic or superconducting lines. If the

transition temperature for superconductors could be raised into the liquid hydrogen range, a far more practical system is possible than that based on scarce liquid helium. There is a further, equally great need for technology for fabricating reliable and economical superconductors. Current methods are prohibitively expensive.

If high pressure hydrogen pipelines become necessary, it will be essential that steels behaving satisfactorily under these conditions be available. In my opinion, no field-welded steel in current pipeline use can be guaranteed fracture-safe when filled with high pressure hydrogen gas.

SYSTEM CONSIDERATIONS

I have touched on only a few of the many energy-related materials areas that I believe warrant your attention. I would like to spend my final few minutes discussing new system approaches that should be studied. Consider a future time production-conversion-transportation-consumption system, where energy is produced remotely from solar, nuclear or thermonuclear heat sources, transported, and finally consumed for the purpose of home heating and cooling, electrical uses in homes, commerce and industry, and for public and private transportation. What would be the optimum overall system for this purpose? I must admit I can't really answer this question, and instead I will show how this would be done with today's technology, and contrast this with what I believe to be very attractive options that should be developed, or at least investigated.

CURRENT TECHNOLOGY

The following comments apply to this system:

1. 60% of thermal energy wasted in conversion at today's efficiencies.
2. Line losses are high for long distances.
3. Private transportation not patterned around electricity; batteries have low energy/unit mass.

Contrast this with an alternate system, which I believe could be developed over the next decade or so:

POSSIBLE FUTURE TECHNOLOGY

The above system appears attractive to me. The two areas that will require the greatest attention are the thermal dissociation of water and the hydrogen-to-electricity fuel cells. Neither of these is Carnot-limited. I hope some of you will be stimulated to conceive other, better systems.

The water-to-hydrogen conversion must avoid the waste of large amounts of thermal energy at the source, where it is usually impossible to utilize. Transportation by high pressure pipeline is fully competitive with electrical transmission at distances greater than a few hundred miles. And if efficient fuel cells can be developed in sizes economical for relatively small areas (such as a few urban blocks) the waste heat can be utilized for space heating and cooling. One advantage of conversion at the point of consumption is that hydrogen/electricity can be consumed in whatever "mix" is most desirable at any time.

I have tried to point out in very general terms a few of the areas where I believe materials science and technology can be best applied to energy systems. As scientists, technologists and engineers we all appreciate the importance of a clean, economical energy in affording a decent life to the people of the world. What greater contribution could we make than to help insure that a continued supply will be available, both in our lifetime and in that of our children?

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