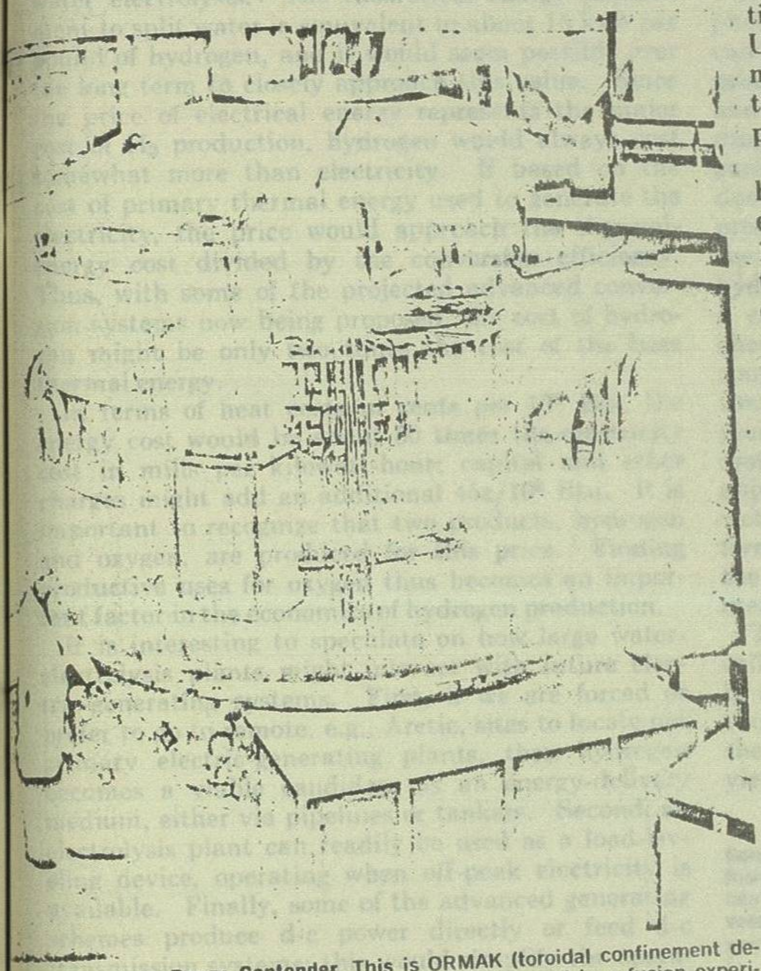

Long-Range Contender. This is ORMAK (toroidal confinement device) in double exposure, a device being used in a fusion experiment that examines the confinement and heating of plasmas intended for fusion power reactors. The composite photograph shows the final assembly of ORMAK, including the completed iron core in the foreground and the frame holding the laser optics in the background. The large ports at center elevation (on left and right) of the tank are for future use with high-current injectors. Construction was completed in January, 1971.

California at Riverside, this writer tilts toward the optimists. At the 1972 Cornell workshop on energy sources,[4] Professor Rex pointed out three possibilities: dry steam, hot water, and hot rock. Dry steam now supplies 192 MW of electricity in northern California at competitive prices. Professor Rex estimates this resource in that part of California at 25,000 MW (although others claim this estimate may be high by a factor of five), and it is not unlikely that other dry-steam fields will be found elsewhere in the west.

Hot-water systems are estimated to be about 20 times as numerous as dry-steam systems and also may be of larger size. Over a thousand have been identified in the U. S. on the basis of hot springs. One of the large ones occurs in the Imperial Valley of California, where Rex estimates the power potential is 30,000 MW. The total power potential in the U. S. from this source is not known, but it is estimated to be between 10^6 and 10^7 MW. The life of the resource is also unknown, but studies in the Imperial Valley suggest this to be 100 to 300 years.

The largest potential for geothermal energy is in hot rock. According to calculations by Rex, the present recoverable reserve in the west is of the order of 10^8 MW-centuries; thus if hot rock can be used for thermal power, most of the U. S. demand for energy could be satisfied thereby.

The big question is, just how feasible is hot rock for power production? Rex proposes the following scheme: Two wells are drilled a few hundred feet apart. The input well might be from 8000 to 20,000 ft deep to reach temperatures of 338 F to 572 F. The output well is perhaps 3000 ft less deep. Hydraulic fracture is used to establish cracks between the wells. Cold, dense water flows down the deeper well and rises convectively through the crack system. The rock loses heat to the water, which expands slightly and rises through the shallower well to the surface. This hot water flows through a heat exchanger on the surface to drive a low-boiling working fluid through a turbine. Rex estimates power costs at around 15 mill/kwh for this system.

This idea is elegant in concept, yet we really don't know whether it can be made to work. Would water injected into the one well come out the other, or would it be forever lost in the bowels of the earth? Would the water that comes up be so laden with crud as to make the whole thing an engineering nightmare? Experimental testing is now underway at Los Alamos, Livermore, and Pacific Northwest to determine how these difficult geological questions can be resolved.

Hydrogen

It seems clear that ultimately mankind will have two energy systems: a primary one depending on either fission, fusion, or solar sources and a secondary system that will take care of portable energy needs. To a growing band of dedicated "hydrogenophiles," this secondary source will be H_2.

The great advantage of H_2 is that it is essentially nonpolluting; if it is burned catalytically at low temperature, its combustion leads only to H_2O. Even when hydrogen is burned with air in conventional internal-combustion engines, H_2 can be controlled to meet the 1975-1976 Environmental Protection Agency standards, including that for NO_x. Further, in nearly all applications hydrogen appears to be capable of substituting for today's fossil fuels. Practical questions then remain: Can widespread use of H_2 be safe? Can H_2 be manufactured, ultimately from water and prime energy, at anything approaching reasonable costs?

Methods of H_2 manufacture—sunlight and biological, heat and enzymes, electrolytic, chemical—should be discussed, if only briefly. The most probable large-scale production process would seem to be

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[4] "Summary Report of the Cornell Workshop on Energy and the Environment," sponsored by the National Science Foundation, Committee on Interior and Insular Affairs, U. S. Government Printing Office, Washington, D. C., 1972.

water electrolysis. The theoretical energy requirement to split water is equivalent to about 15 kwh per pound of hydrogen, and it would seem possible over the long term to closely approach this value. Since the price of electrical energy represents the major cost of H_2 production, hydrogen would always cost somewhat more than electricity. If based on the cost of primary thermal energy used to generate the electricity, the price would approach the thermal-energy cost divided by the conversion efficiency. Thus, with some of the projected advanced conversion systems now being proposed, the cost of hydrogen might be only two times the cost of the base thermal energy.

In terms of heat costs in cents per 10^6 Btu, the energy cost would be about 30 times the electricity cost in mills per kilowatt-hour; capital and other charges might add an additional 45¢/10^6 Btu. It is important to recognize that two products, hydrogen and oxygen, are produced for this price. Finding productive uses for oxygen thus becomes an important factor in the economics of hydrogen production.

It is interesting to speculate on how large water-electrolysis plants might interact with future electric-generating systems. First, if we are forced or prefer to go to remote, e.g., Arctic, sites to locate our primary electric-generating plants, then hydrogen becomes a viable candidate as an energy-delivery medium, either via pipelines or tankers. Second, an electrolysis plant can readily be used as a load-leveling device, operating when off-peak electricity is available. Finally, some of the advanced generating schemes produce d-c power directly or feed d-c transmission systems; this would simplify the operation of an electrolysis plant, which requires large quantities of d-c power. Also, the deuterium required in fusion reactors could be produced as a by-product of water electrolysis.

Processes for hydrogen (and oxygen) production that require only thermal energy are now under active development by Euratom in Europe. These processes use a closed set of four or more chemical reactions so that, with inputs of only heat and water, hydrogen and oxygen are produced; all the reaction products are internally recycled. Similar ideas were intensively studied in this country a few years ago and are currently receiving renewed attention at several laboratories. These production systems seem to be some distance from commercial practice, but if developed they would have the inherent advantage of not first requiring the conversion of thermal to electrical energy for hydrogen production. One must remember, however, that such systems are not without certain inefficiencies, so it is not now clear how these systems may ultimately compare with other methods of production.

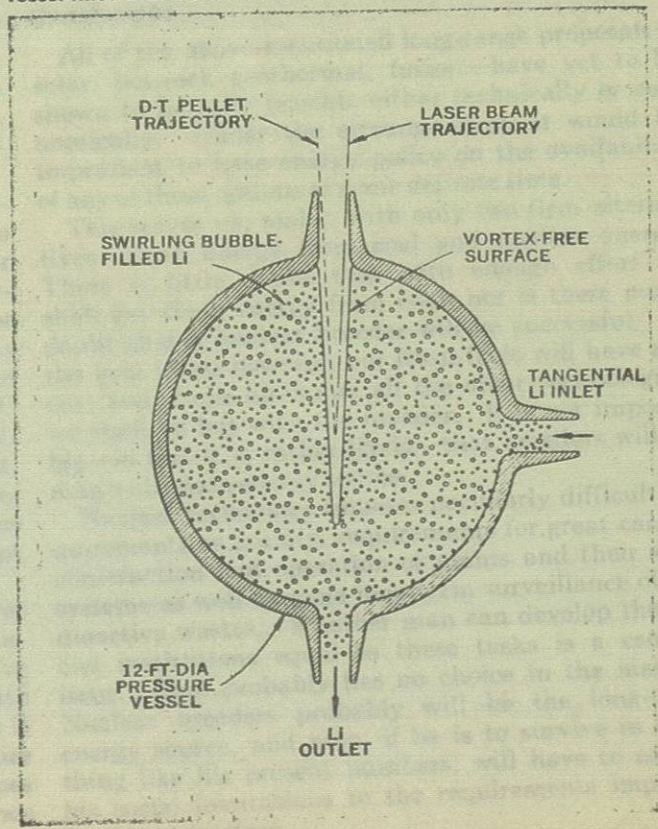
Other Intriguing Possibilities

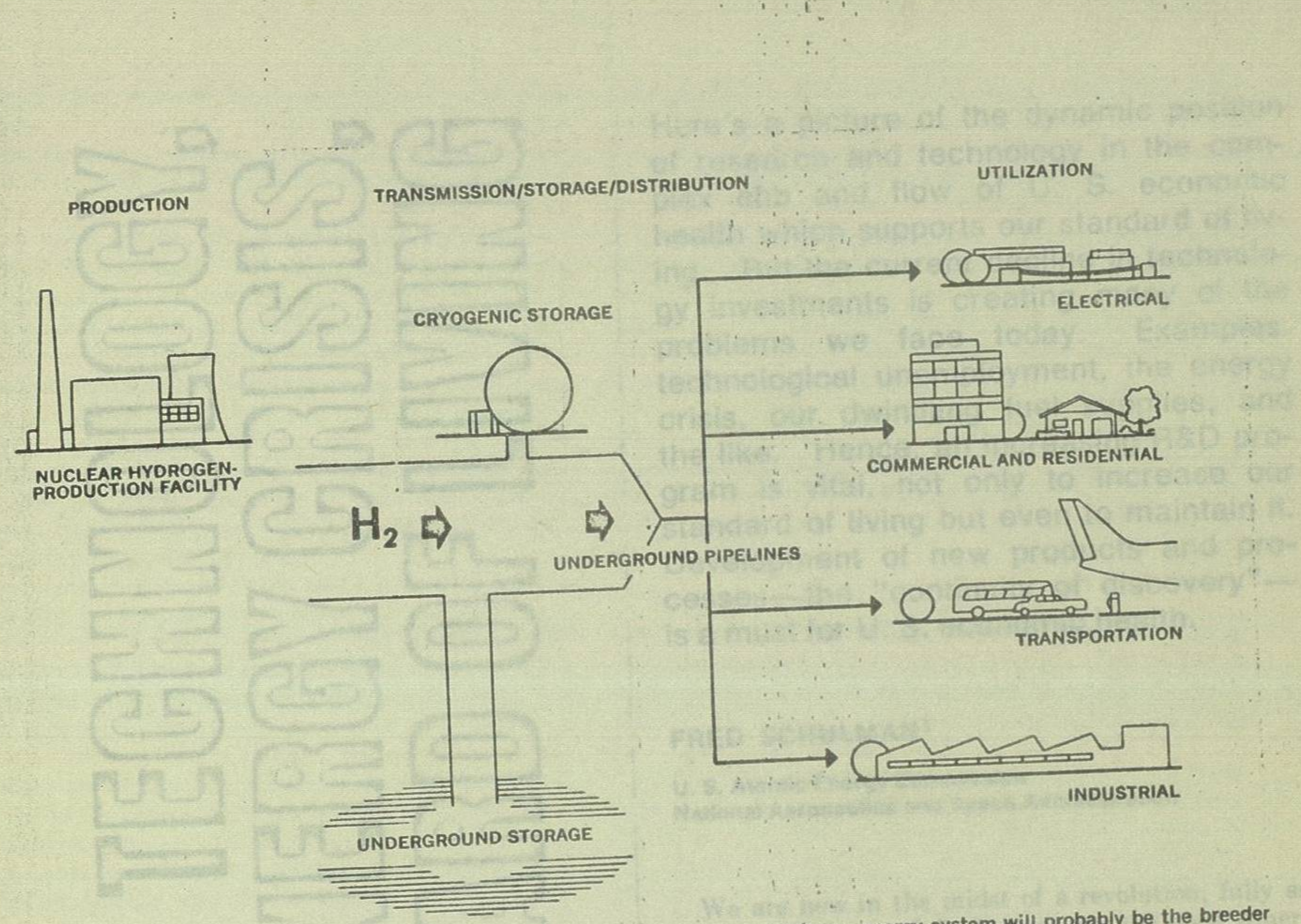
There are some further intriguing production possibilities just now being considered that involve basically biological processes.

It is possible to use photosynthetic organisms in a photochemical fuel cell. Plants and blue-green algae can utilize water as a reductant in light-dependent generation of compounds (such as reduced ferredoxin and viologens) that are equivalent to molecular hydrogen as reductants. In addition, in the living organism, the ferredoxin and ATP are then used to reduce carbon dioxide to cell material. However, the production of cell material is not a necessary step in the harnessing of light energy. Energy storage as hydrogen would be more efficient and direct. Such a conversion could be accomplished if the photochemically reduced reductants (ferredoxin, etc.) were coupled to a hydrogenase. Essentially this process would represent a photolysis rather than an electrolysis of water. The requirements for such an aqueous system would be: light, a stabilized photochemical apparatus capable of generating reductants from water, ferredoxin or a similar electron carrier, and a ferredoxin-coupled hydrogenase. Stabilization of the photochemical apparatus is the critical requirement of this system.

The efficiency of the proposed photosynthetic fuel cell appears to be sufficiently high to be economically useful. Under laboratory conditions, energy-conversion yields of up to 10 percent are encountered in the isolated photosynthetic apparatus. If such yields can be obtained with a stabilized photochemi-

Conceptual design of a fusion reactor that makes use of the fusion reactions occurring when an intense laser beam heats the deuterium–tritium ice pellet within the center of a spherical reactor vessel filled with molten lithium.





Hydrogen Energy System. The hydrogen system is actually a secondary system; the primary energy system will probably be the breeder reactor.

cal system, one readily calculates that of the 0.8 cal/cm²/min of solar energy that strikes the earth's surface every day, the total yield of the proposed photosynthetic fuel cell would be some 500 kcal/m²/day. A 500-ton/day hydrogen-production plant would require an area of 14,000 acres or about 22 sq mi.

What about the safety of widespread use of hydrogen? Most fuels require some care and control, so that fuel substitution becomes a matter of degree or extent of control required. Gas containing 50 percent hydrogen was distributed to urban homes for many years as town or coal gas. Safety problems encountered often stemmed from the non-hydrogen component, carbon monoxide. NASA and the AEC are routinely handling liquid hydrogen in large volume and have compiled an impressive safety record. Hydrogen is extensively pipelined in and around refineries and transported daily as either liquid or gas over our highways and railways—also with excellent safety records.

Some of the basic properties of hydrogen that relate to safety are that its lower explosive limit is similar to that of natural gas (~5 percent), its explosive or ignition energy is relatively low, and its diffusivity is relatively high while its volumetric heat content is one-third that of natural gas. While it will require some care and respect in handling, hydrogen does not appear to be fundamentally more dangerous than many other fuels we use daily.

Conclusions

All of the above-mentioned long-range proposals—solar, hot-rock geothermal, fusion—have yet to be shown to be fully feasible either technically or economically. Under the circumstances, it would be imprudent to base energy policy on the availability of any of these options at some definite time.

This leaves us, really, with only two firm alternatives—clean energy from coal and nuclear energy. There is little doubt that with enough effort we shall get clean energy from coal, nor is there much doubt that a nuclear breeder will be successful. In the long term, however, our fossil fuels will have run out, and if one discounts all the other technologies, we shall be left with the breeder. It is not impossible—in fact it is rather likely—that breeders will be man's ultimate energy source.

Nuclear technology imposes peculiarly difficult requirements on society, requirements for great care in construction and operation of plants and their subsystems as well as some long-term surveillance of radioactive wastes. Whether man can develop the social institutions equal to these tasks is a central issue. Man probably has no choice in the matter. Nuclear breeders probably will be the long-term energy source, and man, if he is to survive in anything like his present numbers, will have to adjust his social institutions to the requirements imposed by this technology.

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