Fuel from Wastes: A Minor Energy Source

ENERGY

At the same time that the United States has begun to consume far greater quantities of fossil fuels than can be produced domestically, it has also begun to produce far greater quantities of solid organic wastes than can be consumed by landfills and other conventional methods of disposal. A great amount of experimental work has indicated that these wastes can be converted into synthetic fuels, thereby apparently solving both problems simultaneously.

Many arguments in favor of such a solution have been highly simplistic, however, and have ignored the difficulties of marketing low-value energy resources. Many proponents of conversion, furthermore, have frequently both overestimated the amounts of suitable waste materials available and underestimated the difficulties of collecting sufficient quantities to make operation of a conversion plant economically acceptable. It is thus clear that, while conversion of organic wastes to fuels is an ideal way to dispose of the wastes, it is probably not a feasible method of averting an energy crisis.

The United States unquestionably generates fantastic quantities of solid wastes—about 1.1 billion tons of inorganic mineral wastes and more than 2 billion tons of organic wastes each year. As recently as a year ago, waste conversion proponents argued that treatment of this organic waste would produce nearly 2.5 billion barrels of oil per year, or roughly half this country's annual consumption. Newer estimates suggest that this number is somewhat exaggerated.

A study prepared for the U.S. Department of the Interior's Bureau of Mines (BuMines) by Larry L. Anderson of the University of Utah indicates that more than half the total weight of these wastes is actually water. In 1971, Anderson says, the total amount of dry, ash-free organic waste produced in this country was only 880 million tons (Table 1). More than 80 percent of that total, furthermore, was so widely dispersed that it could not be used; only about 136 million tons of dry organic wastes were readily collectable for conversion. This amount would have produced 170 million barrels of oil—roughly 3 percent of 1971 consumption of crude oil or 12 percent of imported crude. Alternatively, this amount of waste could have produced 1.36 trillion standard cubic feet (1 scf $= 2.8 \times 10^{-2}$ cubic meters) of methane, about 6 percent of 1971 consumption of natural gas.

There are three major routes for conversion of these wastes to synthetic fuels: hydrogenation, pyrolysis, and bioconversion. Hydrogenation and pyrolysis have been advanced to the pilot and demonstration plant stages of development, respectively, and will probably be commercialized within this decade. Bioconversion has received only a minor research effort, however, and commercialization is unlikely before 1985.

The most highly publicized, and perhaps most promising, conversion method is the hydrogenation process developed by Herbert R. Appell and Irving Wender of BuMines' Pittsburgh Energy Research Center. This process might more aptly be termed a deoxygenation or chemical reduction process, since the principal reaction is abstraction of oxygen from cellulose—the primary component of organic wastes—by carbon monoxide and steam. Like pyrolysis and bioconversion, the process can be applied to virtually all organic wastes.

In the process, organic waste and as much as 5 percent of an alkaline catalyst such as sodium carbonate are placed in a reactor with carbon monoxide and steam at an initial pressure of 100 to 250 atmospheres and heated at 240° to 380°C for as long as an hour. Under optimum conditions, as much as 99 percent of the carbon content is converted to oil—about 2 barrels (1 barrel = 42 gallons $= 1.6 \times 10^{-1}$ cubic meters) per ton of dry waste. In practice, more than 85 percent conversion is normally obtained. Because some of the oil must be used to provide heat and carbon monoxide for the reaction, however, the net yield is about 1.25 barrels per ton of dry waste.

The product is a heavy paraffinic oil with an oxygen content averaging about 10 percent and a nitrogen content that may reach 5 percent when manure is the starting material. Sulfur content is generally lower than 0.4 percent, well below the limits for heating oils applied in many cities. The energy value of the oil is about 15,000 British thermal units per pound (1000 Btu/lb $= 2.32 \times 10^{6}$ joules per kilogram). The widely used No. 6 fuel oil, for comparison, has a combined oxygen and nitrogen content of about 2 percent and an energy value of about 18,000 Btu/lb. The energy value of the raw wastes varies from 3000 to 8000 Btu/lb.

The chemistry of the hydrogenation process has been thoroughly tested in the laboratory, and the Pittsburgh center is now operating a 480-pound-per-day continuous reactor to test the process on various potential substrates. Congress has appropriated $200,000—in addition to $250,000 for further laboratory work—for expansion of the plant to handle 1 ton of animal wastes per day, and an additional $300,000 for design studies for a $1.75 million pilot plant to convert wood processing

Table 1. Amounts (10^6 tons) of dry, ash-free organic solid wastes produced in the United States in 1971. [Adapted from L. L. Anderson, *Bur. Mines Inf. Circ. 8549* (1972), p. 13]

Source	Wastes generated	Readily collectable
Manure	200	26.0
Urban refuse	129	71.0
Logging and wood manufacturing residues	55	5.0
Agricultural crops and food wastes	390	22.6
Industrial wastes	44	5.2
Municipal sewage solids	12	1.5
Miscellaneous	50	5.0
Total	880	136.3
Net oil potential (10^6 barrels)	1098	170
Net methane potential (10^9 cubic feet)	8.8	1.36

and logging wastes to oil. The expanded animal waste plant should be in operation by June of 1973, according to G. Alex Mills, chief of BuMines' division of coal, and the wood waste plant could be built within 2 years. A full-scale commercial plant incorporating the BuMines process for either animal or wood wastes could be in operation by 1980, he estimates.

Many developmental problems remain to be investigated in the pilot plant operations. Foremost among them is evaluation of economic feasibility. BuMines has been extremely reluctant to calculate operating costs of a commercial plant by extrapolation from laboratory work, and has generally justified its work primarily on the value of the product oil ($4 to $5 per barrel) and the cost of conventional methods of waste disposal (as much as $10 per ton). Because of the need for pressurized reaction vessels, however, hydrogenation is clearly the most costly of the conversion technologies.

The principal technical problem to be resolved in the pilot plants is the refinement of methods for handling the solids and introducing them to the reactor under pressure. Other problems include refinement of the process for maximum oil yields, separation of oil from the solids, and minimization of pollution, including control of sulfur emissions and purification of process water. But balanced against any pollution from the conversion facility, of course, must be the tremendous decrease in other types of pollution arising from safe disposal of the wastes.

The second major route for production of synthetic fuels is pyrolysis or destructive distillation. A major disadvantage of pyrolysis is that the process generally produces at least three different fuels—gas, oil, and char, for instance—thus multiplying collection

Speaking of Science

The Decline of the Hubble Constant:

It is my enormous pleasure to ask Allan Sandage to take us on a trip through that enormous dimension of time and space in which he feels at home—Martin Schwarzschild, introducing the Henry Norris Russell lecturer, 138th meeting of the American Astronomical Society, Michigan State University, 15–18 August 1972.

The universe may have started with a big bang, or it may have always been in a steady state. There are few measurements of the nature of the universe, and the most important has been found greatly in error. Allan Sandage presented evidence for the big bang, and announced that new data on the time lapse since the initial explosion give an age for the universe that is consistent with the ages of life, the earth, and the stars. The well-known astronomer from the Mt. Wilson and Palomar Observatories further predicted that within the next 10 years it may be possible to tell whether the universe will keep expanding forever or eventually slow down and contract.

Following the tradition of eminent astronomers such as Russell himself, who laid the groundwork for the understanding of stellar evolution, Sandage spoke eloquently and authoritatively. His presentation touched almost every point in modern cosmology; indeed, it seemed to signal that the study of the evolution of the universe had progressed a step closer toward becoming a full-fledged empirical science. However, some of the arguments made at the end of the talk were clearly speculative, arguments thought by some of the younger astronomers in the hall to be reminiscent of a grand but perhaps less rigorous age of astronomy.

Since Edwin Hubble established, in 1921, that the universe is expanding, it has been known that more distant galaxies recede faster. The constant of proportionality in the relation between the velocity and the distance of a galaxy (the Hubble constant) indicates an age for the universe under certain assumptions about the expansion. With the best techniques of his day, Hubble determined a constant which indicated an age of only 1.8 billion years. But even in the late 1930's this was known to be less than the age of the earth's crust. Either the simple "big bang" model was incorrect, or the Hubble constant was wrong. This famous discrepancy was a prime motivation for the "steady state" model developed by Hermann Bondi, Thomas Gold, and Fred Hoyle, which describes a universe that has no beginning or end, but continuously remakes itself according to a fixed and immutable pattern.

The original measurement of the Hubble constant was in error. In fact, the Hubble constant has changed so often that it is a notable example of a mutable constant. According to Sandage, "It has gone down linearly with time," and has now reached a value that makes the age of the universe consistent with the age of its constituents. The most important announcement at the Russell lecture was that the new age of the universe, estimated from the remeasured Hubble constant, is 17.7 billion years, an age remarkably close to the best estimated age of the galaxies (12 to 15 billion years).

The Hubble constant is difficult to measure because there are random velocities of galaxies in addition to the velocities of expansion. Galaxies receding at such great speeds that these perturbations are insignificant are so far away that their distances are extremely difficult to measure. According to Sandage, "You have to look so far in order to see cosmological velocities that individual stars cannot be seen. So you have to devise a technique to bridge the gap between the place where precision indicators [of distance] exist and where the universe is really expanding without any perturbing effects."

Measurement of distance must be done in many successive steps, beginning with the calibration of Cepheid stars in our galaxy (a peculiar class of variable stars whose brightness can be determined by the cycle of variation in their intensities), next measuring the angular sizes of certain hydrogen regions in galaxies near ours, then using distances of further hydrogen regions to calibrate the absolute luminosities of galaxies having a cosmological velocity. Distance can be determined from absolute luminosities by the inverse square law.

In 1932, Hubble established a value of 530 kilometers per second per megaparsec as his constant (a megaparsec is about 3.3 million light years), but the scales of optical magnitude were not accurate for faint objects because and marketing problems. Because pyrolysis is performed at atmospheric pressure, however, construction and operating costs should be lower than for hydrogenation. Several groups have investigated pyrolysis, including BuMines, but the most advanced process was developed by Garrett Research and Development Company, La Verne, California, the research arm of Occidental Petroleum Corporation.

The Garrett pyrolysis process is part of a complete system designed for disposal of urban refuse. Waste is first shredded and dried, and inorganic materials are removed for recycling or disposal. The organic waste is then reshredded and heated by a proprietary heat-exchanger, developed by Garrett, to about 500°C in an oxygen-free atmosphere. Each ton of refuse produces almost 1 barrel of oil, 140 pounds of ferrous metals, 120 pounds of glass, 160 pounds of char, and varying amounts of low energy gas (400 to 500 Btu per scf). The gas is recycled to provide the oxygen-free atmosphere for pyrolysis and, with part of the char, is burned to supply heat for the process.

The oil thus produced contains about 33 percent oxygen, less than 1 percent nitrogen, and less than 0.3 percent sulfur. Because of the high oxygen content, the energy value of the oil is only about 10,500 Btu/lb. The specific gravity of the oil is about 1.3, however, compared to 0.98 for No. 6 fuel oil, so the energy content is actually about 75 percent that of fuel oil by volume.

Garrett claims to have invested more than $3 million in development of the pollution-free process and has tested it for more than a year in a 4-ton-per-day pilot plant at La Verne. The company recently received a contract to build a $4 million, 200-ton-per-day demonstration plant that will handle all the solid wastes produced by the com-

A New Age for the Universe

certain nonlinearities in photographic plates were not understood. Furthermore, the absolute scale of Cepheid brightness was in error, as discovered by W. Baade in 1952. Correcting these two errors reduced the Hubble constant to about 265. In 1956, it was stated to be 180, then after corrections of Hubble's data for other errors, Sandage estimated in 1958 that the best value was 75. The value Sandage announced at the Russell lecture, based on the first complete remeasurement, was 55 ± 7. Sandage commented quite candidly on the contrast between his estimated error and the enormity of mismeasurement over the years.

> Now that's an incredibly small error, 15 percent of the value. Hubble said his value was good to 15 percent also. HMS [Humason, Mayall, Sandage] said their value was good to 15 percent, and the value of 75 is good to 15 percent. Almost everybody, when quoting distances . . . quotes 15 percent. So that's kind of unrealistic, but Martin Schwarzschild said today that one should always underquote the errors so as to give himself some enthusiasm to continue on with the problem.

The problem of the next 10 years, as Sandage sees it, is to look out to greater distances to see whether the linear relationship between the distance and velocity changes. The largest red shift used by Hubble or Sandage was 0.46, but Sandage thinks it will be possible to find the distances of certain galaxies with red shifts of 0.8. [The red shifts of some quasi-stellar objects (QSO's) are almost as great as 3.] The point of measuring objects with larger red shifts is that they may be far enough away so that the time for light to travel to us is a significant fraction of the age of the universe. If the universe is slowing down because of the braking action of its own gravitational forces, then the speeds of very distant galaxies will be observed as larger than one would expect because they would be observed at the expansion rate of an earlier age; in other words, the Hubble relationship would not be exactly linear. Thus, better data at large red shifts will allow astronomers to determine a second constant, called the deceleration parameter. In Friedmann's equation that describes many cosmological models, a deceleration parameter of −1 indicates a steady state universe, a value of + ½ indicates a flat Euclidean universe, and a value greater than + ½ indicates a universe that is decelerating and will eventually contract. The best value available from the present data (1 ± 1) is not definitive, but slightly favors a "big bang" history for the universe.

After stating so succinctly the outstanding problem that must be solved to ascertain what the future of the universe will be, Sandage ventured the suggestion that there is already enough evidence to determine the past. Though many scientists have questioned whether the very large red shifts of QSO's are really indicative of velocities near the speed of light, Sandage presented some arguments in favor of the traditional interpretation. He then estimated that the light from QSO's with the largest red shifts was emitted before 89 percent of the history of the universe had elapsed. Furthermore, data that Sandage presented in his talk suggested that the 200-inch Mount Palomar telescope should be able to detect QSO's with red shifts larger than 3, but searches for objects listed in the 4th and 5th Cambridge catalogs of radio sources have not revealed any. Looking further out in space is equivalent to looking further back in time, and Sandage suggests that suddenly the objects run out.

> If one could substantiate that a red shift limit of 3 is real, have we actually observed the edge of the universe or the horizon of the universe in time? If so, this would be a fairly decent proof that the universe has not always been the way it is now, that it has evolved. This plus the agreement of time scales [the age of galaxies and the age of the universe] would surely be an indication of an evolution: the world did begin.

While astronomers reared in the oriental cultures express very little interest in cosmology, scientists educated within the western Judeo-Christian tradition continue to be fascinated with questions about the orgin of the world. The Russell lecture ended with a powerful allusion to the religious overtones of that fascination.

> The best text that could be indicated here would be that in the beginning there was darkness upon the deep. There was light, and out of that light came everything that we now observe.

Astronomers, of course, will continue making observations.—William D. Metz munities of Escondido and San Marcos, California. The Environmental Protection Agency will provide 75 percent of the funds for the plant, which is scheduled to begin operation in November 1974. Oil from the plant will be sold to the San Diego Gas and Electric Company, which will invest $150,000 of its own for new facilities to handle it. Operating costs for the plant are expected to be a little more than $8 per ton, about 20 percent less than conventional disposal costs in the area.

A full-scale, 2000-ton-per-day plant to process wastes from a city of 500,000 would cost about $12 million, Garrett estimates. In around-the-clock operation at a municipally financed plant, the firm contends, it would cost $5 per ton of refuse to produce oil and other recoverable products worth $6, even with no credit for waste disposal.

Several other groups—including Monsanto Enviro-Chem Systems Inc., St. Louis, Missouri; Torrax Systems Inc., Buffalo, New York; the Union Carbide Research Center, Tarrytown, New York; and Battelle Pacific Northwest Laboratories, Richland, Washington—are investigating pyrolysis of wastes to produce primarily char and low-Btu gas. With few exceptions, these processes have been developed principally for volume reduction of solid wastes, and production of gas has not been optimized. The low-Btu gas, furthermore, cannot be transported economically and must be used at the production site, which greatly reduces the viability of such processes.

The city of Baltimore, Maryland, for example, with EPA assistance is planning to install a $14 million, Monsanto-designed pyrolysis facility that will handle 1000 tons of solid waste daily. Fuel gas generated in the process will be burned at the site to produce steam that will be sold to the Baltimore Gas and Electric Company for the production of electricity. Even so, operation of the plant is expected to cost nearly as much as would disposal in a landfill. Furthermore, many conventional waste disposal incinerators throughout the country also generate steam, but have been unable to sell it. Oil production is thus a much more desirable alternative.

Production of methane that could be used interchangeably with natural gas is also a desirable alternative, but the cost of upgrading the low-Btu gas produced by pyrolysis is prohibitive. Methane can, however, be produced by the third major technology, bioconversion through digestion by anaerobic bacteria. Development of this process is less advanced than the others, but current work suggests that about 10,000 scf of methane could be produced from each ton of solid waste.

Anaerobic digestion has been used for many years to reduce and stabilize municipal sewage, and EPA is sponsoring some research for that purpose. Only recently has the National Science Foundation also begun to fund energy-directed digestion research as part of its Research Applied to National Needs (RANN) program.

A 3-Year Study at Pennsylvania

The principal recipient of such RANN funds is the University of Pennsylvania's Center for Energy Management, Philadelphia, which was awarded $600,000 for a 3-year study of the feasibility of converting urban wastes to methane. A probable participant in the project will be United Aircraft Corporate Research Laboratories, East Hartford, Connecticut, which has been investigating waste digestion for several years. As the project is outlined by Pennsylvania's Martin Wolf, the university group will study bacterial processes in the digester, control and maximization of gas production, fuel utilization, and environmental considerations, while United Aircraft will focus on actual systems design, component procurement, and operation. Other major investigators include John T. Pfeffer's group at the University of Illinois and Dynatech Corporation, Boston, Massachusetts.

Although bioconversion is theoretically a simpler process than hydrogenation or pyrolysis, a large number of problems remain to be solved. Among them are the need for new techniques to feed solids into the digesters and inexpensive methods for collection and purification of the methane, recirculation of the effluents, and control of pollution. A major environmental problem is disposal of the organic sludge —which may amount to 40 percent of the starting material—that remains after digestion.

This sludge could possibly be dried and burned, but that would produce air pollution problems. It could conceivably be converted to oil or gas through one of the other techniques, but it would then seem more logical to use that technique on all the waste. Or, since the sludge has a high protein content, it might also prove valuable as a raw material for the manufacture of animal feed. Whatever the solution, though, the economics of sludge disposal will play a major role in the overall viability of bioconversion.

If the preliminary investigations suggest that these economics might be favorable, a small NSF-funded pilot plant could be in operation within 5 years, according to the NSF's Lloyd Herwig. A larger, 10- to 100-ton-per-day demonstration plant, possibly funded jointly by federal and local governments and industry, could be in operation in 8 to 10 years. A full-scale commercial plant, he estimates, could be in operation in about 15 years.

From a consideration of energy, each of these conversion methods is severely restricted by the limited amount of solid wastes available. A number of investigators have therefore suggested supplementation of these wastes with algae, phytoplankton, and other plants grown specifically for such use. For now, however, the costs of harvesting and transporting such plants to the conversion facilities appear far too great to justify such an approach. Even on the best land, moreover, the photosynthetic efficiency of farming—the amount of incident energy stored in the crop—is rarely above 0.5 percent.

Much greater efficiencies can be obtained with fast-growing algae in ponds or the ocean. Between 4 and 10 percent of incident light energy can be stored by strains of algae that are now grown outdoors, but efficiencies of at least 20 percent have been achieved in the laboratory. Efficiencies can also be improved by enriching the algal medium with carbon dioxide and ammonia.

Most work on growth of algae has been directed toward their use as an oxygen source in sewage treatment facilities, and even this research has been very limited. More data will be necessary before it will be possible to determine whether algae can be grown cheaply enough for use as a raw material in fuel production. Major problems, many of which will be investigated by the University of Pennsylvania–United Aircraft project, include lowering the construction costs of facilities for growing algae; providing adequate, cheap nutrients, such as sewage, perhaps; and harvesting them efficiently and transporting them to the conversion facility. Even by the most optimistic estimates, it will be at least 25 years before large-scale production of algae could begin to contribute at least 1 percent of this country's energy supply.—THOMAS H. MAUGH II