I

THE PROMISE OF SCIENTIFIC TECHNOLOGY: THE NEW REVOLUTIONS[1]

Our federal government spends $16 billion per year on research and development. At least half of this is spent for military development; about $5 billion for space exploration, $1 billion for health research, $500 million for atomic energy research, and the rest for many smaller scientific and technical enterprises.

The institution to which I belong, the Oak Ridge National Laboratory, spends about $100 million per year. Originally we were concerned entirely with atomic energy, though in recent years we have expanded our scope to include such matters as desalting the sea and civil defense. Many of us whose scientific lives have been involved with one or another of these huge scientific enterprises often ask ourselves, "Is society getting its money's worth from what we, and other Big Scientists, spend?" It will be my purpose in this essay to explain why society could hardly survive for many more generations without the fantastic developments that have

[1]This essay contains material that I first presented in "Energy as an Ultimate Raw Material," *Physics Today 12,* 18–25 (November 1959); in "Today's Revolution," *Bulletin of the Atomic Scientists XII,* 299–302 (October 1956); and in "Effects of Scale on Modern Science and Technology," *Society for Social Responsibility in Science Newsletter* (November 1963).

come out of Big Science. The whole future of our society depends upon the continued success of our science and our scientific technology.

In pursuing this theme, I shall call mostly upon my experience in atomic energy. I do this for two reasons: first, because most of what I know in science and technology relates to atomic energy, and second, because voices have been raised — for example, David E. Lilienthal's in his *Change, Hope, and the Bomb*[2] — casting doubt on the validity of the whole nuclear enterprise. I think it is important that those of us who see in nuclear energy, and in the other marvels of modern science, a means to achieve H. G. Wells's world set free[3] ought to speak out. Our vision of an abundant world is well worth striving for, and it would be even more vigorously sought if only society at large had a clearer idea of the shape of that world.

The Thermodynamic Revolutions

The overriding concerns of society in the next few generations must be the question of peace and the question of population. I shall set aside the first question for the moment and consider only the second. The next twenty-five years may see the world's population rise from its present 3.2 billion to 6 billion. We "should do well to ponder the significance of this development in terms of the destiny of our species.

"These next twenty-five years form part of a process which began some 200,000 years ago and which is about to culminate in man's full possession of the earth."[4]

The most obvious threat of uncontrolled population growth

[2] Princeton University Press, Princeton, New Jersey (1963).

[3] *The World Set Free: A Story of Mankind*, Dutton and Company, New York (1914).

[4] *Population Bulletin XV*, 21, Population Reference Bureau, Inc., Washington, D.C. (March 1959).

is the threat foreseen by Thomas Malthus: population grows faster than do the means of subsistence. Science, at least in the West, has thus far forestalled the consequences of Malthus' dilemma. It has created abundance, and in the United States, the problem-laden affluent society. The question is whether science can continue to maintain the living standard until we learn how to control the population explosion. *Everything I say is therefore predicated on the assumption that we shall eventually control population, hopefully at a size not much more than twice the current population. If we cannot control the growth of population, nothing can save us.*

Malthus' dilemma is, from one point of view, an imbalance between the energy available to man and the energy he requires. For, as I shall explain later, with energy we can convert common materials into the necessities of life: we can convert sea water into fresh water, or nitrogen in the atmosphere into nitrate fertilizer (and ultimately into food), or even coal into gasoline (by hydrogenation with hydrogen obtained from electrolysis of water).

Malthus overlooked a second dilemma. This has to do with the increase in complexity, in the proliferation of the semantic environment, which accompanies the growth of population. As the number of people in a given location grows, the number of semantic contacts between people also grows. In simplest approximation, the number of contacts grows as the square of the number of people. Life becomes more complicated. There are more people to generate ideas, social contacts, personal interactions. The technology of mass dissemination imposes these stimuli upon us with alarming effectiveness. Our newspapers, not to say our scientific journals, get thicker. Our media of communication, including our transportation system, are stretched ever harder. Each individual is exposed to many more sensory impressions than was his father or his grandfather. But our ability to absorb sensory impressions hardly grows: each person merely can know less of what goes on around him, can interact less efficiently with the rest of society. We become specialized in outlook. We experience the same frustration that is felt by the older scientist who, once knowing the whole of a scientific field, must now content himself with knowing a tiny part of it.

A striking example of this "proliferation of complexity" is the telephone system. Whenever a new subscriber is added, the telephone company must add another phone to the system. At the same time, the company must expand the central switching system by a much larger increment so that the new subscriber can communicate with every other subscriber. The complexity of the switching system expands (just as do contacts between individuals) much faster than does the system itself; finally, the switching exchange dominates the whole system. This impasse was anticipated by the telephone companies as early as the 1900's, and led to the introduction of automatic dialing systems. Were it not for automatic dialing, our entire population would eventually consist of telephone operators.

That something like Malthus' second dilemma operates in isolated, overcrowded animal communities is suggested by experiments[5] on the crowding of rats. When well-fed rats are crowded beyond a certain point, they tend to become withdrawn from each other. This manifests itself, among other ways, in a marked reduction in sexual activity, and a consequent reduction of the birth rate.

This second Malthusian dilemma, the dilemma of complexity, is an imbalance between the rate at which semantic stimuli — that is, information — are generated, and the rate at which the individual can respond to the stimuli. It is an *information* crisis, in contrast to the *energy* crisis that characterizes the first Malthusian dilemma.

Ordinarily we think of energy and information as being

[5]V. C. Wynne-Edwards, "Self-Regulating Systems in Population of Animals," *Science 147,* 1543–1548 (1965).

unrelated. Yet they are subsumed in the same scientific discipline, the science of thermodynamics. In order to make this connection clearer, I shall have to give a one-paragraph digression on classical thermodynamics.

Energy is the subject of the first law of thermodynamics. This law says that energy can be neither created nor destroyed, only transformed from one form into another. Entropy is the subject matter of the second law of thermodynamics. The second law says that the entropy of the universe always increases. In more ordinary language, and somewhat inexactly, this is equivalent to saying that the disorder of the universe always increases. We know that things left to themselves decay and disorganize: a house will become unkempt unless tidied every day; weeds will ruin a garden unless they are dug out regularly; heat will flow toward cold unless work is done to reverse the flow. Thermodynamics describes this natural trend toward disorder by saying that the entropy of each of these systems has increased.

The connection between all this and the notion of information was first shown by L. Szilard in 1929.[6] He demonstrated that the information content of a system was the negative of the system's entropy; thus the second law of thermodynamics can be paraphrased: the information content of the universe decreases. In this sense, information can be viewed as the subject matter of the second law of thermodynamics; and Malthus' second dilemma, insofar as it is an information imbalance, is concerned with the second law of thermodynamics, just as Malthus' first dilemma, being an energy imbalance, is concerned with the first law of thermodynamics.

To my mind this statement of Malthus' dilemmas in the language of thermodynamics provides a neatly unified view of the human condition: the future of mankind is destined

[6]L. Szilard, "Über die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen," *Zeitschrift für Physik 53,* 840–856 (1929).

to be a struggle between increasing population on the one hand, and dwindling resources of energy and inability to cope with complexity on the other. But this neat view would be without substance were it not that the two major scientific and technical revolutions of our time are also concerned with energy and information. The energy revolution has suddenly presented us with completely new resources of energy, and should therefore help us to escape from Malthus' first dilemma; at the same time, it will present us with new problems. The information revolution has presented us with new ways of dealing with complexity, and should therefore help us to escape from Malthus' second dilemma, but it also will present us with new problems. Much of this essay will be devoted to examining how these two major scientific-technical revolutions, particularly the energy revolution, can be expected to ameliorate the human condition and how, in some respects, these revolutions will aggravate it.

Energy: The Ultimate Raw Material

I now consider energy and its impact on man. Many books have been written on the subject, most notably by Palmer Putnam and by Hans Thirring.[7] Writers on energy divide into optimists and pessimists. The pessimists hold that cheap and abundant energy is important but not terribly important. After all, only 2 per cent of the Gross National Product of the United States went into generation of electricity in 1964; even if the cost of electricity went to zero, the effect on the entire economy, from this viewpoint, would be minimal. The optimists, such as Harrison Brown,[8] whose views have

[7]Palmer Putnam, *Energy in the Future,* D. Van Nostrand Company, Inc., New York (1953); Hans Thirring, *Energy for Man,* Indiana University Press, Bloomington, Indiana (1958). See also Alvin M. Weinberg, "Energy as an Ultimate Raw Material," *Physics Today 12,* 18–25 (November 1959).

[8]Harrison Brown, James Bonner, and John Weir, *The Next Hundred Years,* The Viking Press, New York (1957).

strongly influenced my own, look upon cheap and abundant energy as central: as the means of resolving Malthus' first dilemma. They view a world with inexhaustible cheap energy as did H. G. Wells — as a "world set free."

I shall expound the optimists' position. First I point out, as did Harrison Brown, that as we exhaust our richer natural resources, we shall have to use more and more energy to extract the necessities of life from common materials: from rock, from the sea, from the air. Thus, although energy now accounts for but 2 per cent of our Gross National Product, it seems likely that this fraction will increase greatly in the future. Only if we can maintain, and indeed increase, our supply of very cheap energy can we hope to stave off the consequences of Malthus' first dilemma in the face of our increasing population. This point was stressed by Sir Charles Darwin in his book *The Next Million Years.*[9] Sir Charles took a very dim view indeed of mankind's future unless we discovered a very cheap and inexhaustible source of energy. I shall therefore describe how the world could extract means of subsistence from ordinary materials reasonably economically, but only if it had cheap and inexhaustible energy. Second, I shall describe the astonishing progress that has taken place, some in the past couple of years, in achieving cheap and inexhaustible energy. My major contention is that although the energy revolution envisaged by H. G. Wells when he wrote *The World Set Free* has all but arrived, we have not yet responded fully to this revolution.

The Importance of Cheap Electricity

Suppose that we have learned to produce electricity anywhere in the world at a price — say, 1.5 mills/kwh — that is as low as the cheapest electricity now available in a few very isolated hydroelectric sites, such as Rjukan in Norway. This

[9]Doubleday, Garden City, New York (1953).

price is about half the price of electricity produced in the best modern publicly owned American coal-powered stations, with coal costing $4/ton, and about four times lower than the cost of electricity in most other parts of the world, where coal costs $10/ton. I shall first show how cheap energy can be converted into the major material requirements of life: water, food, metals, and a tolerable environment.

Consider water. To extract fresh water from the sea by distillation requires a minimum of about three kilowatt hours (kwh) of mechanical work per 1000 gallons. This minimum is achieved if the process is conducted infinitely slowly. In actual practice the process requires ten to fifty times as much work. The simplest and best established process is multiple-effect distillation. In this process sea water is boiled, and the vapor, in condensing, boils additional sea water at lower pressure. This process is repeated successively, sometimes as many as thirty times. By using the heat from the condensing vapor many times, one saves energy; however, one pays in complication of the distilling apparatus. In the United States, several demonstration plants have been distilling sea water for years. The largest such plant, at Point Loma, California, produces 1.4 million gallons of fresh water per day, enough to supply an American town of about 5000 inhabitants.

Distilling sea water is no trick; the problem is to distill it economically — say, for less than 25¢/1000 gallons if the fresh water is to be used by a municipality, or for less than 5¢/1000 gallons if it is to be used generally for irrigation. The cost of water from a desalting plant is made up of two major components: capital cost and energy cost. If the energy is expensive, it pays to save energy by using a complicated, multistage still in which energy gained by condensation in one stage boils water in the next stage. If the energy is cheap enough, it pays to waste energy by using a cheap still with very few stages. This latter possibility has emerged in the past few years, largely from the work of R. Philip Hammond, formerly at Los Alamos and now at the Oak Ridge National

Laboratory. Hammond originally envisaged huge nuclear electrical desalting installations producing 10^9 gallons of water per day and 4000 megawatts of electricity, although he has now designed somewhat smaller units as well. In these dual-purpose plants, heat to energize the evaporators is drawn off from the low-pressure end of the turbines. Since most of the heat so drawn off would be wasted anyhow, it can be provided to the evaporators for almost nothing. Moreover, as will be discussed later, because the installations are large, their *unit* capital costs ought to be very low, although of course the entire plant will be very expensive. Hammond estimates that such large dual-purpose plants operated publicly could produce water for around 15¢/1000 gallons and by-product electricity for about 1.5 mills/kwh.

Hammond's ideas have created a sensation among people interested in desalting and in nuclear energy. President Johnson has launched a Water-for-Peace program to exploit these possibilities and to share our knowledge with water-hungry countries throughout the world. We have already cooperated with the U.S.S.R. in an exchange of information; we are now working with Israel, Mexico, and other arid countries in further exploring nuclear desalting. I have little doubt that within the next decade we shall see several large dual-purpose electricity and desalting plants springing up in arid places bordering the sea. At first these plants will produce water only for municipal or industrial use. As experience is gained in the operation of such large plants, the unit cost ought to fall, until eventually, I believe, water cheap enough for at least some agriculture will be feasible.

I turn next to food, where a primary *technical* problem is to convert energy into fertilizer — that is, into fixed nitrogen, potassium salts, and superphosphate. R. E. Blanco and others of the Oak Ridge National Laboratory have studied this question,[10] and I shall quote some of their results. If the world

[10]R. E. Blanco, J. M. Holmes, R. Salmon, and J. W. Ullmann, "An Economic Study of the Production of Ammonia Using Electricity

were to use fertilizer at the same per capita rate as we in the United States use it, consumption of fixed nitrogen, phosphate, and potassium would increase from the 27 million metric tons used in 1961 to 181 million metric tons by the year 2000. Blanco estimates that the cost of energy needed to fix nitrogen from the air by the arc process, with electricity at 1.5 mills/kwh, is only about 4¢/pound of nitrogen. The total cost of fixed nitrogen, which includes capital and operating costs as well as the cost of energy, might then be as little as 11¢/pound. This is about 50 per cent higher than the present cost of nitrogen, as ammonia, obtained from natural gas and air, though no more expensive than nitrogen from Chile saltpeter. The total cost of the estimated 80 million tons of nitrogen needed by the year 2000, even at 11¢/pound, would be about $18 billion per year, or about $4 for the nitrogen needed to fertilize the crops necessary to feed one person per year.

Potassium salts can in principle be extracted from the sea as a by-product in a sea-water distillation plant. Such processes for extracting potassium are not very economical as yet, but Blanco is optimistic that they can be developed. As for superphosphate, electricity is already used by the Tennessee Valley Authority (TVA) to produce superphosphate from raw phosphate rocks. In 1950 Schurr and Marschak[11] calculated that if electricity were available at 3.2 mills/kwh, superphosphate could be made economically from raw Florida phosphate rocks by electrical rather than by chemical methods. If electricity were cheaper, presumably poorer grade phosphate rocks could be used economically. Raw phosphates are distributed quite widely, and although they seem to be scarce in China and India, the world is well enough endowed

from a Nuclear Desalination Reactor Complex," ORNL–3882, Oak Ridge National Laboratory, Oak Ridge, Tennessee (June 1966).

[11]S. H. Schurr and Jacob Marschak, *Economic Aspects of Atomic Power,* Part Two, Chapter VI, "Phosphate Fertilizers," 124–134, Princeton University Press, Princeton, New Jersey (1950).

with phosphate rock in many places to supply this raw material for a very long time.

To summarize, with electricity at 1.5 mills/kwh and using as raw material only air, sea water, and phosphate rock, we probably could produce fertilizer that is only about 50 per cent more expensive than the cheapest fertilizers now available. Moreover, this source of fertilizer is essentially inexhaustible. In this sense, cheap electricity could indirectly provide sufficient food to keep up with the population, at least for a considerable time.

Conversion of electricity into metals is a similar story. All the important metals appear in nature as oxides, the metals having lost their valence electrons. To obtain metals from ores, one must supply electrons. In the smelting of iron ore, electrons are supplied by coke. In principle, electrons can be supplied directly by electricity, or less directly by hydrogen, which is produced from the electrolysis of water. The direct cost of the energy is negligible; at 1.5 mills/kwh, the cost of energy would still add only about two tenths of a cent to the price of a pound of iron. Unfortunately, the needed technology for direct reduction of iron is not developed (although electrolytic reduction of aluminum is a well-developed art). However, electric furnaces in which electricity supplies heat to a mixture of low-grade coke and iron ore have been used to reduce iron ore on a fairly big scale. The advantage of such furnaces is that they use a low-grade, generally abundant coal rather than the high-grade coking coal needed for blast furnaces.

Eventually we shall have to get metals from lower and lower grade ores. Harrison Brown examined this matter several years ago.[12] He concluded that the cost of the energy

[12]H. Brown and L. T. Silver, "The Possibilities of Securing Long Range Supplies of Uranium, Thorium and Other Substances from Igneous Rocks," *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy 8*, 129–132, United Nations, New York (1956).

needed for crushing and hauling rocks from which very low-grade metallic oxides could be extracted was high but not intolerable. He estimated that the energy from about 25 kilograms of coal would be needed to process a ton of granite, but that from this ton of granite one could eventually extract 70 kilograms of aluminum, 10 kilograms of iron, 4 grams of uranium, and 13 grams of thorium. Of course, one would not use common rock as raw material for a long, long time; however, it is reassuring that Brown's estimates suggest that we can get metals, particularly uranium and thorium, from the rocks if only our energy is cheap enough.

If one considers supplying electrons directly to reduce metallic ores to their metals and supplying electrons via elemental hydrogen, the latter is probably the more promising. If hydrogen is sufficiently cheap, it can be used to advantage not only to win metals from ores but also to fix nitrogen as ammonia, or to convert coal into liquid fuels. Thus, the full utility of cheap energy as the ultimate raw material for heavy chemical processing may depend strongly upon our devising cheap ways of electrolyzing water into free hydrogen and oxygen. Here the needed processes seem to have received an unexpected boost from both military and space technology. Compact fuel cells for spacecraft have been developed in which current densities at the electrode approach 1000 amperes per square foot. This is about five times the current density achieved in large-scale electrolytic cells now used for manufacture of hydrogen. If these high-current-density electrodes could be applied to large-scale electrolysis, presumably the unit capital costs could be drastically lowered, and the way to cheap hydrogen via cheap electricity, and then to reasonably priced metals, fertilizer, and liquid fuel, would be fairly clear.

Finally, I mention energy for space heating. Again I draw upon Brown, who estimates that eventually two thirds of the world's space heating will be supplied by solar heat, the rest being provided by electricity. In the TVA area, where elec-

TABLE 1

PROJECTED ENERGY INPUT PATTERN FOR YEAR 2060
(After Brown, Bonner, and Weir[8])
(World Population 7×10^9)

Source	Equivalent Metric Tons of Coal (Billions)	Equivalent Heat Energy 10^{18} Btu*	Mwy† Heat
Solar energy (for 2/3 of space heating)	15.6	.42	140×10^5
Hydroelectricity	4.2	.10	38×10^5
Wood for lumber and paper	2.7	.07	24×10^5
Wood for conversion to liquid fuels and chemicals	2.3	.06	21×10^5
Liquid fuels and petrochemicals produced via nuclear energy	10.0	.27	90×10^5
Nuclear electricity	35.2	.96	320×10^5
	70.0	1.88	633×10^5

*Btu — British Thermal Unit, 252 calories.
†Mwy — Megawatt year.

tricity for heating costs only 7 mills/kwh, electrical heating is competitive with heat from coal. Of course for house heating, even if electricity were *generated* at 1.5 mills/kwh, its cost to the consumer would be much higher — say, 5 mills/kwh. Still, at 5 mills/kwh, electric heating would probably compete with heat from fossil fuel in much of the United States, and we therefore can look forward to the day when many of our houses will be heated with electricity from nuclear reactors.

I recapitulate by giving a projected energy budget for the world of 2060 drawn up by Brown, Bonner, and Weir in their book *The Next Hundred Years*.[13] These authors assume that

[13]Harrison Brown, James Bonner, and John Weir, *op. cit.*

the world's population will be 7 billions at that time, and that most of the types of conversion of energy into materials I have described, other than distilling of sea water, are feasible. If sea-water distillation is included, Brown's energy budget would probably increase by 10 or so per cent.

The total projected yearly consumption of energy, 6.3×10^7 megawatt years of heat, is the equivalent of 70×10^9 tons of coal per year, or 10 tons per person. This is about eighteen times the present equivalent energy input of 0.35×10^7 Mwy of heat. At Brown's ultimate rate, the present fossil fuel reserves of perhaps 2400×10^9 tons would hardly last fifty or so years. Thus, we must take for granted the world's ultimate dependence on some source of energy other than fossil fuel.

The Nuclear Energy Revolution: Cheap Energy

Most of the public awareness about energy has been focused on nuclear energy, and of course I shall return to its role. However, our interest in nuclear energy ought not to cause us to overlook the remarkable advances that have occurred in the technology of conventional power. Thermal efficiencies have crept up steadily each year until now new large stations operate routinely at better than 40 per cent efficiency. Units have become larger and larger, and several plants are now under construction in the United States in which a single turbine and boiler produce 1000 megawatts of electricity (Mwe). As the plants become larger, their unit capital cost falls: the new 615 Mwe Cardinal Plant of the American Electric Power Company cost $107 per kilowatt of electricity (kwe) in 1964, though a duplicate plant, built in 1966, is estimated to cost $125/kwe. Advances in transmitting electricity have also been spectacular. Voltages are up to 750 kilovolts, and Consolidated Edison Company of New York has considered transmitting 2 million kilowatts of electricity from hydroplants in Labrador, a distance of 1200 miles. The technology of mining and hauling coal is improving rapidly, possibly under pressure of competition from nuclear energy. The Joy Manufacturing Company has developed a prototype automatic coal mining machine that in a day can mine as much coal as can several hundred miners. The railroads have developed new bulk carriers — "unitrains" — which drastically reduce the cost of hauling large amounts of coal. The result of all these incremental gains is that modern privately owned steam plants in much of the United States now generate power at around 4.5 mills/kwh. If the plants are publicly owned, so that the annual charges are 7.5 per cent instead of the 13.5 per cent assessed on privately owned plants, the cost of generation would be reduced by around 0.9 mill/kwe.[14]

[14]Philip Sporn, former president of the American Electric Power Company, in a talk before the Southern Interstate Nuclear Board, Oak Ridge, Tennessee, January 20, 1966, gave the following estimate of the current economic status of coal-fired power plants.

THE PRESENT ECONOMIC STATUS OF COAL-FIRED POWER BASED ON EXPERIENCE WITH THE CARDINAL STEAM PLANT (AS OF 1966)

	Cardinal-Type Coal-Fired Unit
Capability (Mwe)	615
Unit Capital Cost $/kwe	125
Heat Rate (Btu/kwhe)*	8650
Capital Charges at 80% Load Factor, 13.5% Annual Charges (mills/kwhe)	2.4

	20¢/MBtu†	25¢/MBtu	30¢/MBtu
Fuel (mills/kwhe)	1.73	2.16	2.60
Operating and Maintenance (mills/kwhe)	.30	.30	.30
Energy Cost (mills/kwhe)	4.43	4.86	5.30

*kwhe — kilowatt hours of electricity.

†MBtu — million Btu. Coal at $4.80/ton corresponds to heat energy at about 20¢/MBtu, assuming the energy content of the coal is 12,000 Btu/pound.

But nuclear energy has moved even more rapidly. As recently as 1963, the nuclear technology community was rather pessimistic about the prospects for nuclear energy's becoming competitive. One quip had it that "nuclear energy would become competitive within 10 years of the time the prediction was being made." Most of us could not see how the capital costs of nuclear plants could be reduced much below $200/kwe, and at this price, nuclear energy would not be competitive. However, since 1963 several spectacular happenings have completely changed the outlook.

The first was the announcement early in 1964 by the Jersey Central Power and Light Company that it had contracted with the General Electric Company for a 515 megawatt boiling water reactor to be built at Oyster Creek for the extraordinarily low (by nuclear standards) price of $132/kwe. If the reactor could be operated at its "stretch" rating of 620 Mwe, the unit capital cost would fall to $109/kwe, which is lower than the price of most conventional electric plants of this size. This announcement created a sensation. The sensation was compounded when, in fairly quick succession, firm price bids for many other large nuclear plants were announced: Altogether, as of the middle of 1966, our country's utilities have contracted for 21 million kilowatts of nuclear generating plants. The largest of these is the 2.2 million kilowatt TVA plant at Browns Ferry, Alabama, that is expected to generate electricity at about 2.4 mills/kwhe under TVA financing conventions. A coal-fired plant of the same size was estimated by TVA to generate electricity at 2.8 mills/kwhe. This is particularly significant since TVA lies in the heart of the Appalachian coal country and enjoys the benefit of very low-priced coal.

What happened so suddenly to make nuclear energy competitive? Of course, one must remember that all of these new plants are still to be completed. And there is a chance that the plants will not operate as well as expected. But the good operating experience of the Yankee Atomic Electric plant, a pressurized water reactor operating since 1960 at 185 Mw, and the Dresden No. 1, boiling water plant operating since 1959 at 210 Mw, puts the likelihood of failure very low. Certainly the private utility companies that have bought these new reactors are willing to invest their own money in pressurized and boiling water nuclear reactors.

Of the factors that seem to be involved in this drastic reduction of the cost of nuclear power plants, three stand out.

First, the Oyster Creek boiling water reactor is the sixth or seventh of a series of reactors of this type. It is inevitable that designers of a series of reactors, all of the same general type, find ways of improving each successive reactor. For example, the steam that is generated directly in the core of the new Dresden No. 2 boiling water reactor is separated from entrained water in the pressure vessel itself, whereas in Dresden No. 1, the steam is de-entrained in a separate, and expensive, steam drum.

Second, there is the working of the competitive market place. The market for large civil water reactors in the United States is now dominated by the General Electric Company, which favors the direct boiling water system, and by the Westinghouse Electric Corporation, which favors the pressurized water type. Both companies have bid on every major nuclear power installation. One can hardly doubt that the spirited competition between these two giants has lowered the price of the current crop of reactors.

Finally, and perhaps most important, the new reactors are all very large (the two new TVA reactors are designed to generate 1100 megawatts apiece). As has been stressed most strongly by Hammond, large nuclear reactors are much cheaper, per unit of output, than are small ones. This comes about because a nuclear reactor is, in principle, an unlimited energy source; the amount of heat that can be drawn from the reactor is limited in principle only by the size of the heat-exchange equipment and the maximum temperature of the reactor. The cost of a nuclear reactor increases as its power output increases, but not as fast as its output. The cost of the reactor itself (its instrumentation, its shield, its control room, and so on) hardly increases at all as the output of the reactor increases. The cost of the heat-exchange equipment increases with heat output, but, like most large-scale equipment, at a slower rate than the heat output itself. Thus the cost per kilowatt will fall as the output of the reactor increases. That the unit cost of nuclear reactors, like the cost of conventional power plants, decreases with increasing size is now attested to by price lists established both by General Electric and Westinghouse.

The other major component of cost in the nuclear reactor, the fuel cycle cost, also seems to fall as the size of the system increases. The fuel cycle cost is made up of four components: carrying charges for the fuel inventory, fabrication of the fuel elements, burnup of the fissile material, and chemical processing to recover unburned fuel. Most of these costs fall sharply as the scale of the operation is increased, at least for reactors that use natural uranium or reactors that efficiently convert the abundant U^{238} into Pu^{239}. Moreover, fabrication and chemical processing, not to speak of separation of the fissile U^{235} from nonfissile U^{238}, are operations that lend themselves well to mass production. If these enterprises are conducted on a large enough scale, then the costs approach more and more nearly the cost of the raw materials, chemicals, and power. Such reduction in cost has been strikingly demonstrated at the great diffusion plants in Oak Ridge, Paducah, and Portsmouth that separate U^{235} from natural uranium. Because U^{235} is separated on such an enormous scale, a gram of separated U^{235} now costs only about four times as much as its initial cost as unseparated isotope. Estimates based on demonstrated performance of the huge fabrication and reprocessing plants at Savannah River and at Hanford suggest that, if a standardized fuel element were used, and reprocessing could be done for a group of reactors producing altogether 25,000 or, better, 50,000 megawatts of heat, the fuel cycle costs for certain nuclear reactors could be as low as one tenth the fuel cost of coal. Herein lies the great economic advantage of nuclear reactor power plants as compared with fossil fuel plants. The basic fuel cost in a nuclear system is potentially extremely low; in some breeder reactors the fuel cycle cost is estimated to come to around 0.2 mill/kwhe, whereas very few coal-burning plants have fuel costs as low as 1.7 mills/kwhe.

Where do these projections finally lead? The over-all cost of energy from the Oyster Creek plant was estimated by Jersey Central to be less than 4 mills/kwhe. This estimate is based on rather low fixed costs (10.4 per cent instead of the usual 13.5 per cent), high load factor (88 per cent instead of the more usual 80 per cent), and a fuel cycle cost of 1.5 mills/kwhe, which Oyster Creek is not expected to reach until its third fuel loading has been burned. If the annual charges are taken as 13.5 per cent and the load factor is 80 per cent, the cost of energy would be around 4.4 mills/kwhe, which still is a little lower than Sporn's 1966 estimate of the cost of energy from the coal-fired Cardinal plant.

But I believe these estimates are only a beginning, and that important reductions are in sight. The largest saving should come in the fuel cycle; here, for the reasons I have already mentioned, the fuel cycle, operating, and maintenance costs ought to fall to 0.5 mill/kwhe or less. The capital cost, if the plants are even larger than the ones now being built (say 3000 Mwe), could in my opinion plausibly fall to $90/kwe. The total cost of electricity, from a privately owned plant operating at 80 per cent load factor, might then be as little as 2.5 mills/kwhe.

Nor is this the plausible lower limit. For if these very large plants were base-loaded, and particularly if they were used to supply energy for chemical processes, the load factor might be 95 per cent, not 80 per cent. Moreover, there is a good chance that plants of this sort might last much longer than the thirty years on which their amortization rate is calculated.

Once the plant is written off, the fixed charges might fall below 10 per cent, and the out-of-pocket cost for operating such plants would be very low indeed. In any case, if the plant is publicly owned, so that it pays no taxes, the annual charges would be around 7.5 per cent, and the over-all power cost would approach 1.5 mills/kwhe.

A word should be said here about the difference between the cost of electricity at the generating plant and its price to the consumer. It is true that the price to the consumer, including transmission, maintenance of distribution system, and so forth is usually much higher than the actual cost of generation. However, as the customer's load increases, the difference between generating cost and sales price diminishes. For example, the large gaseous diffusion plants in Oak Ridge, which have used as much as 2 thousand megawatts of electricity, paid essentially the generating cost to TVA for this huge block of power. Since the uses, such as large-scale chemical processing, would involve very large blocks of power, and the chemical plants would be close to the source of power so that transmission would be very cheap, 1.5 mills/kwhe is not an implausible assumption for the ultimate cost of power actually used.

When first put forward, the prediction that nuclear energy from large publicly financed plants would cost around 1.5 mills/kwhe was so astonishing and, if correct, could have such profound effect, especially on the possibility of economically desalting the sea, that the matter was reviewed by a committee in the United States representing the Atomic Energy Commission, the Department of the Interior, and the Federal Power Commission. The triagency study[15] concluded that energy from extremely large publicly owned nuclear power plants might well sell for as little as 1.6 mills/kwhe. This is the lowest price for energy from a thermal plant ever

[15]"An Assessment of Large Nuclear Powered Sea Water Distillation Plants," prepared for the Office of Science and Technology, U.S. Government Printing Office (March 1964).

projected in a responsible government study. To many in the nuclear energy community the estimate seems amply justified by the technical situation.

The Nuclear Energy Revolution: Inexhaustible Energy

How long will our sources of energy last? At the rate of consumption projected by Brown, coal, if used as a major energy source, would last only fifty or so years. The situation is even less favorable if we are to depend on the U^{235} contained in very cheap uranium ores. The entire energy content of U^{235} derived from cheap uranium ore is probably only a few per cent of the energy content of the world's coal.

However, there are two other sources of energy — one remote, the other very real — which are inexhaustible. The first is the controlled thermonuclear fusion of deuterium, or "burning the sea." The energy content of all the sea's deuterium is infinite for all practical purposes, about 10^{10} times Brown's yearly energy budget. However, in spite of much experimentation throughout the world, no one has been able to create the conditions necessary to burn deuterium in a controlled way. These conditions are formidable: a temperature of one billion degrees (at which temperature matter is converted into plasma — that is, a collection of independently moving positive ions and electrons), a pressure of 50 atmospheres held solely by a magnetic field, and a residence time of the swiftly moving deuterium ions of a second or so. Under these extreme conditions the plasma tends to be unstable; it moves wildly toward the confining walls and dissipates itself. The outlook for eventually learning how to stabilize the plasma and ultimately how to burn the sea fluctuates from year to year. At the moment physicists have learned how to eliminate the gross "macroinstabilities" of the plasmas by imposing peculiarly shaped magnetic fields, the so-called "Ioffe" fields (named after the Russian physicist who first demonstrated experimentally that such fields suppress gross instabilities). However, there are a host of subtler "micro-instabilities" that must be eliminated before one can even begin to say whether controlled fusion will ever be feasible, or if it is, whether it will ever be an economical way of producing energy.

There is another, much more immediate possibility for achieving an inexhaustible source of energy. This is the breeding of fissile U^{233} or Pu^{239} from the all but inexhaustible uranium and thorium contained in the granitic rocks. In the breeder reactor, more fissile material is created from ordinary uranium or thorium than is burned. The breeding process therefore makes every nucleus of uranium and thorium, not just the rare light isotope of uranium, a potential source of energy. As a consequence, uranium ore, which is too expensive to use if only the U^{235} contained in it is burned, becomes an economical fuel. The resulting multiplication of our nuclear energy potential is enormous: first, by the factor of about 400, which represents the ratio of the number of thorium and U^{238} nuclei found in nature to the number of U^{235} nuclei; and second, by the enormously greater factor of perhaps 10^8, representing the ratio of the total amount of uranium and thorium in the accessible parts of the earth's crust to the amount of cheap uranium ore. The total energy content of the residual uranium and thorium in the accessible granites is fantastic — of the same order as the total energy content of the deuterium in the sea. Thus a cheap, practical breeder would provide a permanent, essentially inexhaustible source of energy just as much as would controlled fusion. Moreover, since low-grade deposits of uranium and thorium are ubiquitous, cheap energy eventually would be available in every portion of the globe.

Of course, we would not be driven to "burning the rocks" — that is, using the residual 10 or so parts per million of thorium and uranium in granite — for many, many years. There are vast amounts of uranium and thorium in the rocks at concentrations of 50 or so parts per million. For example, the Conway granites in New Hampshire contain some 30 million tons of thorium at an average concentration of about 50 parts per million. K. B. Brown and his group at Oak Ridge have developed methods of extracting this material at a cost estimated to be only about $35/pound. Even at this price, which is about eight times the current cost of uranium, the burnup cost in a breeder reactor would be less than .02 mill/kwhe. Since, at Harrison Brown's ultimate energy budget, one is burning about 40 tons of fissile material per day, the 30 million tons of thorium contained in the Conway granites alone would last for a very long time indeed — say, a couple of thousand years! Moreover, the mining operation required to supply the world with 40 tons of thorium or uranium every day would not be unreasonable. If this material were supplied by the Conway granites, only one million tons of rock would have to be mined and processed each day. This is but one fourth of the world's 1952 daily production of coal and lignite.[16] The whole mining operation required to sustain the ultimate energy economy would be smaller than the mining operation that now sustains the much smaller, fossil-fuel-based, world energy economy! But these extraordinary possibilities rest on the development of a successful breeder reactor. It is for this reason that I view the development of a practical breeder to be one of the most important technological jobs facing mankind.

Fortunately the technical outlook for a successful, economical breeder reactor is good, even though most of the world's effort in nuclear energy has not gone toward developing breeders. Five experimental breeder reactors have been built, three in the United States, one in the United Kingdom, and

[16] UN Department of Economic and Social Affairs, "World Energy Requirements in 1975 and 2000," *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy 1*, 3, United Nations, New York (1956).

one in the Soviet Union. Several more are scheduled to go into operation within the next half dozen years, among the largest being a 250 Mwe installation on the Caspian Sea that will energize a desalting plant as well as produce electricity. One of the most successful breeder reactors so far has been the one built at Dounreay, Scotland. This machine has operated well at 60 Mw of heat. Its performance has given the United Kingdom Atomic Energy Authority confidence to plan a much larger breeder. In the United States, the nuclear energy effort will probably shift more and more to the development of breeder reactors, and I am confident that a breeder reactor that produces electricity economically will be operating within ten to fifteen years. I believe this achievement would have to be ranked as of extraordinary importance in the history of mankind, only a little less important than the discovery of fission. It certainly would be as important as would the achievement of controlled fusion.

Some among my readers will accuse me of exaggerating when I predict a resolution through nuclear breeding of the competition between population and resources, a resolution that one hopes will give us at least some of the time we need to learn how to control our population permanently. Yet I believe I am not unduly optimistic. I do not, for example, have to invoke nuclear fusion as have others who have speculated on these matters. I have based my judgment on a technology — nuclear breeder reactors — that is really close at hand. The new age of energy is here, and the extravagant claims made for nuclear energy when it was discovered are really coming to pass.

The Revolution in Information

Science seems to be coming through, again in the nick of time, with ways of dealing with the second Malthusian dilemma: the increase in complexity, that is, the imbalance between the individual's capacity to understand and the proliferation of his semantic environment. The underlying scientific achievement — what the late Norbert Wiener called the cybernetic revolution — has many aspects: automation, digital computation, efficient communication, and, perhaps most important, identification of information as an underlying issue in the science of biology. My knowledge of information technology is inadequate, and so I shall content myself with describing a few of the developments in the handling of information with which I am familiar. I shall then examine what we might expect of these developments in helping to resolve the second Malthusian dilemma.

What is happening in automation and digital computation astounds and astonishes. I have still not quite recovered from SKETCHPAD, a device for engineering drafting demonstrated to me at M.I.T.'s Lincoln Laboratory. Imagine a cathode-ray screen, like a TV tube, on which one can "draw" lines with a rather standard device called a "light" pen. Now suppose you are an engineer designing a bridge. You draw, freehand, the trusses, but as you draw, your slightly imperfect lines are replaced by perfect, straight lines, each matched as nearly as possible to the freehand lines. You now insert with a typewriter a number designating a weight at a certain point on the bridge. Immediately the stresses in every truss and member of the bridge appear! SKETCHPAD is not confined to bridges; it can sketch, and compute, electronic circuits, or linkages, or for that matter, a girl's face. It can twirl the linkage so that the engineer can better visualize its working, or it can wink the girl's eyes to amuse the engineer.

This is not all. Already computers are being designed, and components developed, with memories of 10^8 words and nanosecond access time. A single such computer, with satellites spread throughout a research establishment, could simultaneously make out the payroll, operate an experimental reactor, and calculate relativistic wave functions. It gives one the eerie feeling that E. M. Forster's machine is practically here, and raises the specter, as did Forster, of what happens when the machine stops.[17]

The resolution of Malthus' dilemma of energy imbalance offered by the discovery of nuclear fission is relatively clear. Moreover, the cybernetic revolution also helps resolve the energy imbalance. Mass production and automation have greatly increased the number of commodities that we can produce and have enabled us to convert our available energy more efficiently into things we need. Unfortunately, the solution to the second Malthusian dilemma, the imbalance between the proliferating semantic environment and the individual's semantic mechanism, is less clear, partly because the technology of information is younger, and partly because the problem of the proliferating semantic environment is more complex.

For the information revolution adds to the proliferation of the semantic environment at the same time it helps us cope with it. The automatic telephone system complicates the life of the housewife who may now spend several hours each day speaking with her friends. Yet, as I have said earlier, only because the system has become automated has the telephone system as a whole remained viable. Without automation we could not have the complexity that automation itself keeps under control. Though automation displaces workers, many of the jobs from which they are displaced (such as the operation of telephones) are jobs that, without automation, the workers could not do.

One consequence of our proliferating semantic environment is a trend toward specialization. In science the fragmentation caused by the scientific information "crisis" has evoked much attention from government and from the community of scientists, and I shall enlarge on this matter in

17"The Machine Stops," *The Collected Tales of E. M. Forster,* 144–197, Alfred A. Knopf, New York (1947).

Part II. The specialization that has afflicted science almost surely must come to the rest of society, if it has not already come. We, each of us, will be able to understand a smaller and smaller fraction of our semantic environment, and in this sense our social organism must fragment. As I shall describe later, one response of science to this specialization has been the emergence of a hierarchy of scientific generalists who spend their time reviewing and compacting literature for their specialist colleagues. Such generalists may have counterparts in society generally. Our lawmakers, in a way, are generalists, as are our newspaper people. And, just as our scientific generalists have trouble keeping up with the details of science, so our lawmakers and newspapermen have trouble keeping up with the details of the society. A U.S. senator from California today represents seventy-five times as many constituents as did one in 1850. He is a generalist of much higher order than was his early predecessor.

Can the technology of information help the generalist maintain sensitive touch with the details of our society? Already it has done much; our central government would be unthinkable without the telephone and the airplane. We begin dimly to see new ways in which the computers with enormous memories might serve the generalist. Computer science today is barely twenty years old. It is not entirely science fiction to imagine, say, a central computer with a memory of 10^9 words, shared by congressmen and connected to satellite computers spread among the constituency. Should a congressman want to ascertain his constituents' views on a subject, he could canvass them ever so much more rapidly and completely than is now possible. Moreover, he could ask complicated questions, and the computer, if properly programmed, could seek out those elements of the answers that would really help him in making up his mind on a crucial issue.

Recently we have come to realize that information is a central concern of the biological sciences. This may have even more effect on our control of the semantic environment than will the computers. Evidence begins to accumulate that the human brain itself may have certain elements that resemble a computer, and that either RNA or some protein may be the essential memory element. J. V. McConnell and his co-workers[18] at Michigan claim that flatworms fed RNA extracted from other flatworms trained to traverse a maze are themselves able to learn the maze better than the controls (although this claim has been challenged by other workers, notably M. Calvin); H. Hydén and E. Egyházi[19] in Sweden claim that the chemical composition of RNA in the Deiters' cells of rats trained to do a balancing act is affected by the training; and D. E. Cameron and L. Solyom[20] in the United States claim that the memories of persons suffering from cerebral arteriosclerosis are significantly improved when RNA is added to their diet. It is too early to say that these findings will be sustained, but it is hardly idle to speculate that many of the mechanisms of the brain will be elucidated, say within a generation, and that from this may come ways of improving the efficiency of our own brains. No matter how good our computers become, human brains finally must monitor their output, must inject the quality of imagination denied to the computer. I feel a little more comfortable about the 10^9 word computers since I see a hope that science might help us improve the working of our own brain-computer, and thereby enable us more effectively to monitor the information robots. We may learn to redress the imbalance between the semantic environment and our individual semantic mechanism not only by using very large computers more cleverly but, perhaps, by making ourselves cleverer.

[18]"Memory Transfer through Cannibalism in Planarians," *Journal of Neuropsychiatry 3*, Supplement 1, S–42–48 (August 1962).

[19]"Nuclear RNA Changes of Nerve Cells During a Learning Experiment in Rats," *Proc. Natl. Acad. Sci. U.S. 48*, 1366–1373 (1962).

[20]"Effects of Ribonucleic Acid on Memory," *Geriatrics 16*, 74–81 (1961).

The Tainted Revolutions: The Applied Scientists' Responsibilities

I have painted an optimistic picture of science's capabilities for resolving Malthus' two great dilemmas. This optimism must be tempered, however, because the solutions offered by science are imperfect; in solving these problems, science creates others. The solutions offered by the two great scientific revolutions centering around energy and information are tainted.

The most obvious taint is the bomb. Nuclear explosives, together with our clever methods of delivery, have given man a relatively easy way to destroy most of what he has. At this stage in the thermonuclear era, one no longer argues about whether the thermonuclear weapon is a blessing in disguise or an unmitigated catastrophe. One simply states to which camp he belongs; I belong to the optimistic camp. I attribute to the bomb the role of peacemaker. The peace we have, tenuous and incomplete as it is, is infinitely better than large-scale war. The simple, unsophisticated notion that the bomb-deterrent has bought us the time we need to get used to the idea of settling international squabbles without large-scale war seems to me to be nearer the actual situation than are any of the more sophisticated views, all of which tend to underestimate the strength of man's instinct for self-preservation.

And, indeed, I believe the energy revolution does have the possibility of helping to stabilize the bomb-imposed, unstable equilibrium. Residual uranium and thorium are available in all the granitic rocks everywhere on earth. When breeder reactors have been developed, every nation, large or small, that can put together the capital to buy the necessary reactors can have abundant and cheap energy. From these central energy sources can flow water from the sea, metals, even liquid fuel. Thus eventually the difference between have and have-not nations, insofar as these differences are based on disparity in natural endowment of raw materials, ought to diminish. And is it not at least plausible that a world no longer beset with widespread hunger and privation, a world afraid to use its nuclear weapons, would be largely a peaceful world?

How this might come about is suggested to me by the effect of nuclear desalting technology on the Middle East. Before desalting technology was recognized as being available to Israel, destruction of the Jordan River Project made a kind of sense to Arab nations bent on destroying Israel. But with desalted water available at about the same price as water from the Jordan system, such action loses much of its point. I would therefore be rash enough to predict that before the century is out, water as such will no longer be a basis for rivalry between Arab and Israeli, and that the disappearance of this source of conflict will eventually lead to improvement of the political climate in the Middle East.

A second taint is the one exemplified in the dramatic writings of the late Rachel Carson: the increasingly serious physical insults to the biosphere imposed by our industrial civilization. Miss Carson spoke only of insecticides, which are needed to help us grow enough food yet which poison our biological environment. But the Rachel Carson problem is only one example of the contamination of our environment that seems to accompany each of our attempts to reduce the imbalance between resources and population. The TVA's Kingston Steam Plant, rated at 1.6×10^6 kilowatts, emits about 400 tons of SO_2 per day into the atmosphere, as well as appreciable amounts of radium. The nuclear reactors I have described create toxic radioactive wastes. Our automobiles help create smog. The whole environment is assaulted by civilization's garbage, and unless curbed, these assaults finally reach the biological world. Before any optimistic view of what science can do to control the Malthusian dilemma is to be taken seriously, one must demonstrate that these taints can be avoided or otherwise dealt with.

I find reason to be hopeful on two accounts: first, we shall learn how to remove the physical insults to the biosphere, and second, we shall learn how to correct the biological damage such insults may cause. With respect to removing the insults, I mention, for example, the very real possibility of economical, pollution-free, electric automobiles. George Hoffman,[21] formerly of the RAND Corporation, has pointed out that the zinc-air battery, one of several types now under development, could provide an ordinary automobile with a range of about 200 miles and a top speed of 95 miles per hour. D. Friedman[22] has recently described a lithium-chlorine electrochemical engine with a specific energy (watt hours per pound) very close to that of a gasoline engine. Its fuel cost, if electricity for recharging were available at 6 mills/kwh, would be competitive with gasoline at 10 cents per gallon! Hoffman is distinctly optimistic about cheap batteries becoming available, and I believe big nuclear reactors eventually will provide electricity to the consumer at less than the 6 mills/kwhe needed to make the electric automobile economical.

Another insult about which much has been said publicly is the possibility of contaminating the environment with the radioactive wastes from large reactors. But routine and safe disposal of radioactive wastes has proved to be simpler than had originally been expected. For example, at Oak Ridge radioactive wastes mixed with cement are being pumped 1000 feet into the ground, there to set permanently along fracture planes between beds of rock. As nearly as geologists can determine, these sheets of radioactive concrete will remain completely out of contact with the biosphere until long after

[21]G. A. Hoffman, "The Electric Automobile — An Example of Vehicle Systems Design," Report MR-54, University of California, Los Angeles (December 1965).

[22]D. Friedman, "The Correlative Advantages of Lunar and Terrestrial Vehicle and Power Train Research," Society of Automotive Engineers, Automotive Engineering Congress, Detroit, Michigan (January 1966).

their radioactivity has decayed. And there are many other feasible schemes for disposing of radioactive materials from reactors, safely and permanently — for example, in unused salt mines or in specially built concrete vaults.

On the matter of radioactive hazard from an inadvertent runaway of a large reactor, such an occurrence can hardly be completely ruled out just as one cannot rule out the possibility of a jet airliner crashing into Yankee Stadium at the height of a World Series game. But major advances have been made in the engineering of "containment" shells, the airtight domes that house nuclear reactors. The general idea is to enclose one containment shell by a second shell, and to keep the space between the two shells below atmospheric pressure. This gas space is continually monitored, so that if any radioactivity appears in the space, it can be handled safely before it escapes to the outside. Generally I am extremely optimistic about dealing with our nuclear garbage, so much so that I believe nuclear plants will displace fossil fuel plants not only because they are cheaper but also because they are cleaner. This seems to have happened in Dade County, Florida. The Florida Power and Light Company, in announcing its decision to build two 750 Mwe pressurized water reactors at Turkey Point, near Miami, explained that only with nuclear plants could the utility meet the stringent requirements imposed by local ordinances regulating the contamination of the atmosphere by power plants.[23]

But there will always be residual physical insults to the biosphere. Is it likely that biologists will learn how to cope with such unfortunate sequelae of exposure to toxic chemicals or radiation as leukemia or gene mutation? Here one can only speculate. The recent discovery of viruses in chemical- and radiation-induced leukemias,[24] and the finding of ways to

[23]McGregor Smith, et al., "Nuclear Power," A Panel Discussion by Utility and Government Experts, Southern Interstate Nuclear Board, Oak Ridge, Tennessee (January 1966).

[24]A. H. Upton, et al., "Observations on Viral, Chemical, and

confer immunity against leukemogenic viruses in experimental mice,[25] are too striking to allow anything but optimism. Many workers in the field believe that the leukemias, now the least tractable of the cancers,[26] ought to be the first curable cancer. Should this take place, science will have removed one of the taints associated with science's solution to Malthus' first dilemma. As for mutagenesis, recent work suggests that,[27] by inspecting prospective parents' chromosomes, pathologists of the future might identify aberrations that would lead to some birth defects. This work is barely beginning, but its possible implications are very exciting.

The huge size which seems to be required of nuclear reactors if they are to be as cheap as I have postulated is an obvious imperfection in the solution offered by nuclear energy to Malthus' first dilemma. If, in order to produce energy cheaply, a nuclear reactor must be much larger than can be accommodated by existing economic and social organizations, then, unless these organizations are merged and enlarged, we shall have to forgo the economic advantage of bigness. This point is an extension of one made by John von Neumann[28] in 1955. Von Neumann, concerned mostly with the H-bomb and with weather modification, pointed out that the geographic impacts of these technologies are so vast as to have rendered

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Radiation-Induced Myeloid and Lymphoid Leukemias in RF Mice," *Journal of the National Cancer Institute* (in press, 1966).

[25]Mary Alexander Fink and Frank J. Rauscher, "Immune Reactions to a Murine Leukemia Virus. I. Induction of Immunity to Infection with Virus in the Natural Host," *Journal of the National Cancer Institute 32,* 1075–1082 (1964).

[26]K. M. Endicott, *Hearings before a Subcommittee of the Committee on Appropriations,* Eighty-Ninth Congress, Department of Health, Education, and Welfare, Part 3, National Institutes of Health, pp. 324–402, U.S. Government Printing Office, Washington, D.C. (1965).

[27]M. Bender, private communication. Also, Robert S. Ledley and Frank H. Ruddle, "Chromosome Analysis by Computer," *Scientific American 214,* 40–46 (April 1966).

[28]"Can We Survive Technology?", *Fortune 51,* 106–108 (June 1955).

obsolete our fragmented political and geographic entities. He suggested that unless the world accommodated to this characteristic of modern technology by closer cooperation between political units, if not reorganization into much larger units, the world could not long survive. Von Neumann was concerned mainly with the impact of military gigantism on our political organizations; I am concerned with the impact of energy gigantism on our economic organization. I believe in both cases the influence of the technology is toward a merging and melding of the relevant political or economic units.

Actually, the economical size of nuclear reactors no longer seems as enormous as it did even in 1960. At that time, a power plant of 500 Mwe was very large indeed. Today, as I have already said, there are a half dozen power plants under construction in the United States with capacities of 1000 Mwe. Moreover, as the over-all size of an electrical system increases, the size of each individual unit on the system tends to increase roughly in the same proportion. A single unit producing 2000 Mwe as part of a station generating 6000 Mwe hardly seems so bizarre; within a decade such plants very probably will be built.

As the size of each unit increases, the penalty that society must pay for technological error increases. This was illustrated dramatically during the 1965 power failure in the Northeast. Here a failure in a huge, interconnected electrical grid system caused considerable social harm, not to speak of loss of property and possibly life. Obviously the scientists and engineers who design such devices bear a heavy social responsibility — heavier, say, than that borne by an architect who designs a small dwelling. My own impression is that the nuclear and electrical engineers will respond adequately to this responsibility by engineering more safety and reliability into their reactors and by analyzing system connections so that a failure in one part of the system will not cause failure in the entire system. The various parts of interconnected electrical grids will probably be tied together more rationally;

at least, the strongly interconnected electrical grids such as the TVA system seem to be more resistant to total failure than are the weakly interconnected systems composed of many independently operated utilities such as were involved in the Northeast incident.

Ordinarily in discussing this aspect of the social responsibility of the scientist, we stress the *recognizable* dangers to society that result if the scientist errs. The tendency then is to put pressure on the technologist or scientist not to try his new schemes because of their evident danger. This is the force of the argument with respect to insecticides, or with respect to the hazards of radioactivity, or the danger of catastrophic collapse of an electrical system. But there is an obvious other side to the story: the *inevitable* catastrophe that society faces because of Malthus' first dilemma, if science and technology do nothing. As I have tried to demonstrate, cheap and abundant nuclear energy is no longer a luxury; it will eventually be a necessity for maintenance of the human condition.

Thus a central social responsibility of the scientist and technologist is to remove the taints, the imperfections inherent in the big technologies needed for mankind's ultimate survival. The task will require reactor and electrical engineers who can reduce the probability of accident to the vanishing point; it will require sanitary engineers and ecologists and chemical engineers who effectively cope with the noxious effluents; and finally, it will require biologists and medical researchers who seek ways of mitigating the biological effects of whatever residual contamination of the biosphere is inevitable.

The Tainted Revolutions: The Humanists' Responsibilities

I suppose I am less hopeful, if not less clear, about the taints associated with the cybernetic revolution — science's contribution to the resolution of the second Malthusian dilemma. Automation and computers, as well as abundant energy, lead to more leisure and to more boredom, and these are taints just as surely as are smog and radioactivity. In earlier times, man's primary concern was economic; making a living was a full-time job. As John Galbraith puts it, "... for those who are poor, nothing is so important as their poverty and nothing is so important as its mitigation. . . . And since for nearly all time nearly all people have lived under the threat of economic privation, men of all temperament and views have stressed the controlling and permanent influence of economic need on social attitude."[29] But the cybernetic and energy revolutions suggest that we shall have to modify this observation and say, "For those who are rich, and have leisure, and are bored, nothing is so important as boredom, and nothing is so important as its mitigation."

For the problem of boredom per se, science can supply its brand of antidote. Science, as one of man's supreme intellectual achievements, shares many of the attributes of the arts. And science practiced widely as high culture, as a means of filling empty lives, is surely desirable; but it seems more likely in the immediate future that the arts and the humanistic studies must continue to play the larger role in filling the vacuum created by our taint of too much leisure. I can therefore see the social responsibility of the humanist as being analogous to the social responsibility of the scientist: the scientist primarily to undo the physical taints of the new revolutions, and the humanist to undo the moral taints of the new revolutions.

I use the word "moral" advisedly, for boredom is the lesser of the psychological evils stemming from our new technology. Of greater concern is the "meaninglessness" of human life, which has become a preoccupation of our modern theologians, notably Paul Tillich. To previous generations survival was so arduous that in itself it gave a certain purpose to life. Few men had the time, or even the extra physical energy, to con-

[29]John Kenneth Galbraith, "Economics and the Quality of Life," *Science 145*, 117–123 (July 10, 1964).

cern themselves with life's larger meaning and purpose; to those who worried about the matter, religion was an adequate answer. With our new leisure, as well as our new knowledge, the ultimate questions of meaning and purpose can no longer be submerged because we are too busy. We are not busy, and the historic central practical purpose of human life — economic survival — is no longer sufficient to sustain us.

To reinject meaning and purpose into our lives, all of us must turn to those who traditionally have carried this responsibility, the humanists. How they shall do this I, a scientific administrator, can hardly suggest. Yet do it they must. We scientists, even as we set about correcting the physical defects of our technical revolutions, can only pray that the humanists will supply those deeper values which up to now Western man has had no time to cherish, but which in the future he will have too much time to survive without.