THE COMING AGE OF NUCLEAR ENERGY

Exciting prospects of food factories in the desert and the use of nuclear energy for industrial processes rivalling in importance the achievement of the first chain reaction were among the forecasts of Alvin M. Weinberg, Director of the Oak Ridge National Laboratory, at the eleventh session of the General Conference. His lecture on "The Coming Age of Nuclear Energy", with its emphasis on the task of producing really cheap energy, was one of the three in a scientific series

Twenty-five years after Enrico Fermi and his associates at Chicago established the first chain reaction, nuclear fission has become a major source of energy, fully competitive with conventional energy sources. To some this means that we ought now to dismantle the world's nuclear energy research establishment: "The major aim of nuclear energy — competitivity with conventional fuel — has been achieved", so the argument goes. "It is time to redeploy the research establishments responsible for this achievement toward more pressing matters that are unrelated to nuclear energy."

I disagree with this thesis. Magnificent as have been the achievements of the first 25 years of fission research, these are only mileposts. There is a new and largely unexplored dimension in nuclear energy — the achievement of truly low-cost energy through the advanced breeder reactor, and the application of this cheap, ubiquitous energy to industrial pro cesses that may rival in importance the achievement of the first chain reaction itself. The nuclear energy enterprise has not fulfilled the atom's promise until the really cheap energy producer, the advanced breeder reactor, has been developed, and its applications to many new processes have been exploited. These are the main tasks for the next generation.

HAS NUCLEAR ENERGY ACHIEVED ITS FIRST GOAL ?

The first goal of nuclear reactor development was a safe, reliable energy source that was competitive with fossil fuels. Has this goal been reached?

Since nuclear energy has developed unevenly and incongruently in various countries, it is difficult to give a single answer to this question that holds for all situations. Briefly, the development has gone along two separate paths: one based on enriched fuel and hydrogen moderator as in the USA and USSR; the other, based on unrenriched or very slightly enriched fuel and enriched or at least low cross-section moderator, as in the United Kingdom, France and

Canada. Both lines of development have now reached a point where large nuclear plants have become articles of commerce. The total nuclear capacity now installed, under construction, or on order in the United States, United Kingdom, and France is given in the following table.

TOTAL NUCLEAR CAPACITY
(Millions of Kilowatts)

Country	Installed	Under Construction	On Order	Total	% of Total Central Electric Capacity
United States (August 1967)	2.8	11.6	29	43.4	17
United Kingdom (November 1966)	3.4	3.3	1.5	8.3	18
France (November 1966)	1.1	1.6	0.3	3	11

Perhaps it is premature to insist that nuclear energy has achieved its first goal — competitivity with fossil fuel — in the United States. After all, none of the second generation of pressurized water or boiling water reactors has begun routine operation. San Onofre, a 430.000 kilowatt pressurized water reactor, has experienced some startup troubles with its turbines; and Oyster Creek, the boiling water reactor that set off the wave of buying, is not scheduled for operation until 1968. Moreover, the very low cost of Oyster Creek, in the region of $110 per kilowatt of electricity will not be repeated in the near future. Recent water reactors have been sold for more like $135/kwe in the United States or even more. But, even after the cost increase, the Tennessee Valley Authority (TVA) has ordered a third nuclear reactor, for its Brown Ferry station, that is expected to generate electricity for about 2.75 mills per kilowatt hour.

The availability and plant capacity factor (energy generated in a year/energy generated if operated continuously at full capacity) during 1966 of the six large light water reactors in the United States is summarized below. Since most of these reactors are load-following rather than base loaded, or, in the case of Shippingport, are used for experiments, availability rather than plant capacity factor is perhaps the better measure of their reliability.

Though several of these reactors had their troubles in 1966, Dresden and Yankee, the two that most nearly represent prototypes of the current American line of light water reactors, had good records. Thus we are looking forward with confidence to the reliable operation in the United States of the new generation of water reactors. To this degree we can say that nuclear energy in the United States, based on light water moderated reactors, is now competitive with energy from fossil fuel.

AVAILABILITY OF U.S. REACTORS DURING 1966

	Capacity (Mwe)	Availability (%)	Capacity factor (%)
Shippingport	90	96	67
Dresden I	200	97	80.2
Yankee	175	89.5	85.8
Indian Point	265	67.5	50.3
Humboldt Bay	68.5	74.9	36.5
Big Rock Point	72.8	88.9	55.3

THE DEVELOPMENT OF COMPANION TECHNOLOGIES

At the same time that nuclear energy has become competitive, three other energy-intensive technologies — agriculture, desalination, and electrolytic production of deuterium, a heavy isotope of uranium — have made important advances. These companion technologies coming at the same time that we are enjoying such success in nuclear energy greatly magnify the importance of the achievements in nuclear energy.

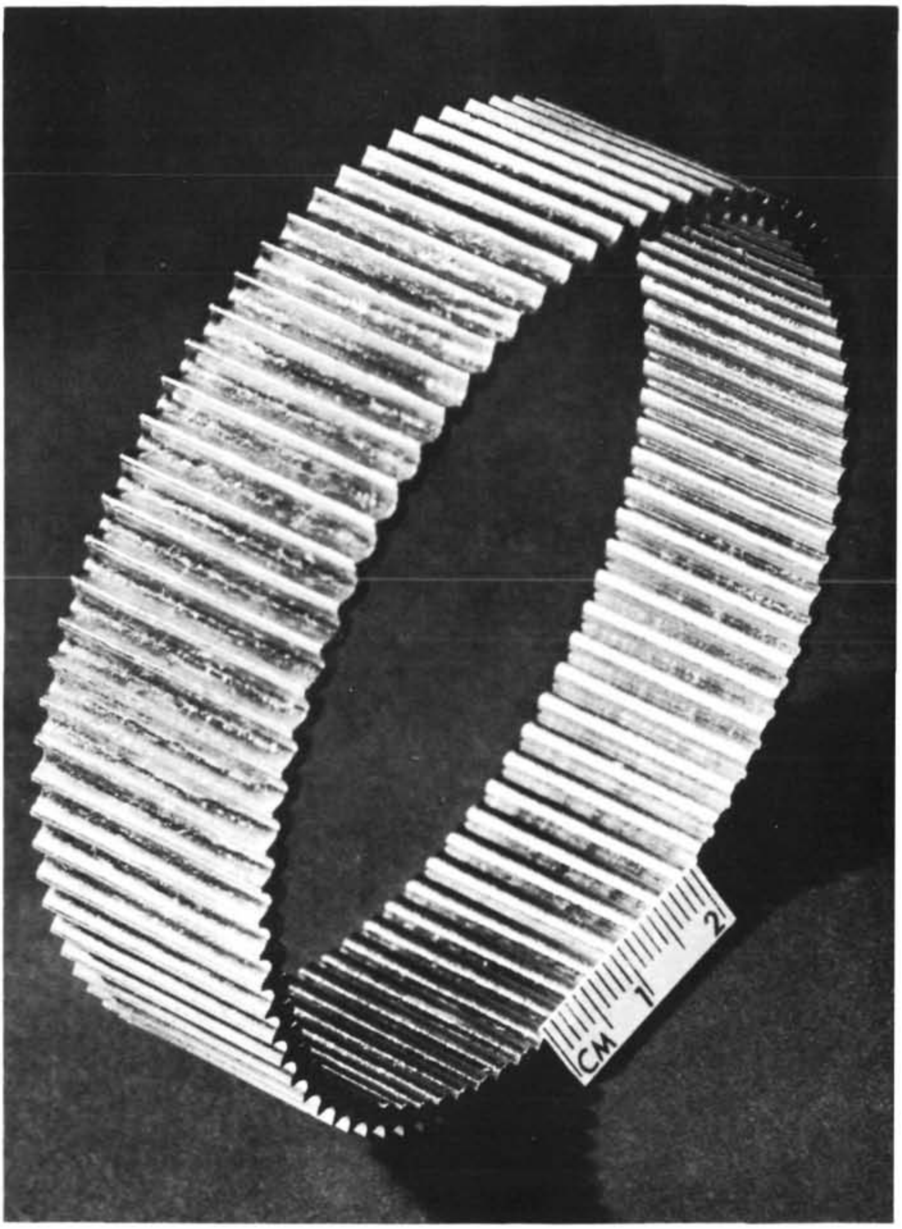
First, and perhaps most important, are the extraordinary new varieties of wheat and rice that have been developed, largely under the sponsorship of the Rockefeller and Ford Foundations and the Mexican Government. The new short-stemmed, rust-resistant, high-yielding varieties of wheat are now widely used in Mexico. Their use had converted Mexico from a wheat importer to a wheat exporter. Fortunately these wheats can be grown in Pakistan (where they are known as Mexi-Pak wheat) and in India as well. But to achieve the very high yields of 100 bushels per acre, the wheat plants must be watered amply and at the right time; and the crop must receive large amounts of fertilizer, particularly nitrogen. Thus in order to take full advantage of these potentially very high-yielding crops, one needs reliable and abundant sources of water and of nitrogenous fertilizer. Fortunately the energy-intensive technologies of extracting fresh water from the sea, and of manufacturing electrolytic hydrogen (and thence ammonia) have moved forward with gratifying speed.

Consider the situation with respect to desalting the sea. The thermodynamic minimum work required to extract 1000 gallons of fresh water from the ocean is about 3 kwh, or, at 30% efficiency of converting heat into work, about 30,000 British thermal units. In an actual distillation process considerably more needed — in modern designs of evaporators about a million Btu of heat go into the production of 1000 gallons of fresh water. The present state of the technology is represented by the Metropolitan Water District plant in Los Angeles. There a dual-purpose plant will produce 150 million gallons of water per day and 1600 megawatts of by-product electricity. The water is expected to cost about 22 cents per 1000 gallons, and the by-product electricity, produced by light water reactors, will cost about 2.7 mills per kilowatt hour.

But the technology is moving very fast. For example, fluted tubes, developed by the General Electric Company, can transfer three times as much heat as do the conventional smooth tubes used in the evaporators designed for the Metropolitan Water District plant. Moreover, it now appears as though a combination still in which the main evaporator uses vertical tubes, and only the feed water is heated by flash evaporator stages, is more economical than the more conventional flash still. Our estimates suggest that water from a 250-million-gallon-per-day, dual-purpose plant that utilizes fluted tubes, such as shown in Figure 1, would cost around 15 cents per 1000 gallons (at 6% fixed charges). Water at less than 10 cents per 1000 gallons seems to us ultimately achievable, if the reactor powering the still can produce power at, say, a mill/kwh less than Oyster Creek-type reactors.

USING THE ELECTRICITY

The by-product electricity in a dual-purpose distillation plant has always been rather an embarassment. One attractive use for this by-product electricity would be the electrolytic production of hydrogen, which is so important for many heavy chemical processes. Fortunately there has been an important recent advance in the technology. I refer to the demonstration of electrolytic cells capable of sustaining current densities of 1600 amperes/square foot, a good factor of 10 higher than the current densities customarily used for large-scale electrolytic production of hydrogen. This advance in technology is a by-product in part, of the space enterprise: such high-current electrodes are used in fuel cells that power auxiliaries in space craft. The application of the fuel cell technology to large-scale electrolytic production of hydrogen has been considered by the Allis-Chalmers Research Division. Based on a report by Allis-Chalmers, we have estimated that, with such high-current density cells and 2 mill power, Section of an evaporator tube, in which double fluting has increased heat transfer three times to improve desalination methods.



a 1000 ton/day ammonia plant ought to produce ammonia for about $30/ton. This is competitive with ammonia from naphtha costing $22/ton.

Can these technologies — the new agriculture, water distillation, and ammonia via hydrogen electrolysis — be combined to significantly increase the world's production of food? A recent remarkable paper by R. Philip Hammond suggests that this might indeed be the case. Hammond considers a highly rationalized agriculture based on distilled water in a fertile coastal desert. He assumes 20 inches of distilled water used for a crop of wheat; and he assumes the yield of wheat to be 75 bushels per acre, a good but not record yield. Then the amount of water required to produce the 2500 calories of food necessary to sustain a man in good health turns out to be less than 200 gallons per person per day! Thus, even with water costing as much as 15 cents per 1000 gallons, the cost of the water required to feed a man comes to around 3 cents a day. This is about cheap enough to be tolerable even for an underdeveloped Malthusian society! (Luckily the cost of the necessary ammonia fertilizer turns out to be much less than 3 cents a day.)

FOOD FACTORIES IN THE DESERT

One can now visualize a new kind of desert agriculture, conducted in units so highly rationalized as to be designated "food factories" rather than farms. In these food factories, plants would be watered and fertilized at precisely the right time, and in precisely the right amounts. Fortunately fertile coastal deserts suitable for such food factories occur in many parts of the world.

The food factory would naturally be accompanied by other energy-intensive chemical processes, particularly those based on electrolytic hydrogen. I have already mentioned production of ammonia; one could imagine other processes such as reduction of iron ore by hydrogen, or electrolytic refining of bauxite to produce aluminium, or production of caustic and chlorine, and thence polyvinyl chloride (PVC) plastics. Altogether what one contemplates is the nuclear powered agro-industrial complex already alluded to by Chairman Seaborg in his opening remarks. This summer we conducted at the Oak Ridge National Laboratory a study under the guidance of Professor E.A. Mason of the Massacusetts Institute of Technology to examine in some detail just what such a nuclear powered agro-industrial complex might look like.

Even this near term complex, based on energy from light water reactors, seems surprisingly attractive. In this complex, a variety of crops would be grown on 140,000 acres of irrigated desert. Ammonia, phosphorous from phosphate rock, caustic, chlorine, and salt would be manufactured. The total investment (including a 2000 Mwe reactor and a 500 million gallons a day desalting plant) comes to about $900 million. The annual value of products produced is $330 million, of which $100 million are agricultural products. The profit on the venture is computed to be $136 million per year, or 15% of the capital investment.

THE NEXT STAGE IN NUCLEAR ENERGY DEVELOPMENT

I believe that the nuclear powered agro-industrial complex may well become an impressively powerful instrument for development. But is is idle to speak of the agro-industrial complex unless the main ingredient — the cheap and reliable reactor — is available.

It is reassuring that, in our study of the near term agro-industrial complex, the venture appeared fairly sound economically even when based on light water reactors. But the full advantage of nuclear power ought to become apparent when the complex is powered with an advanced breeder reactor. For the elasticity of demand of electricity for energy-intensive processes ought to be very high: that is, with power available at, say, 2 mills/kwh, many more industrial processes will be performed electrically than with power at 3 mills—kwh.

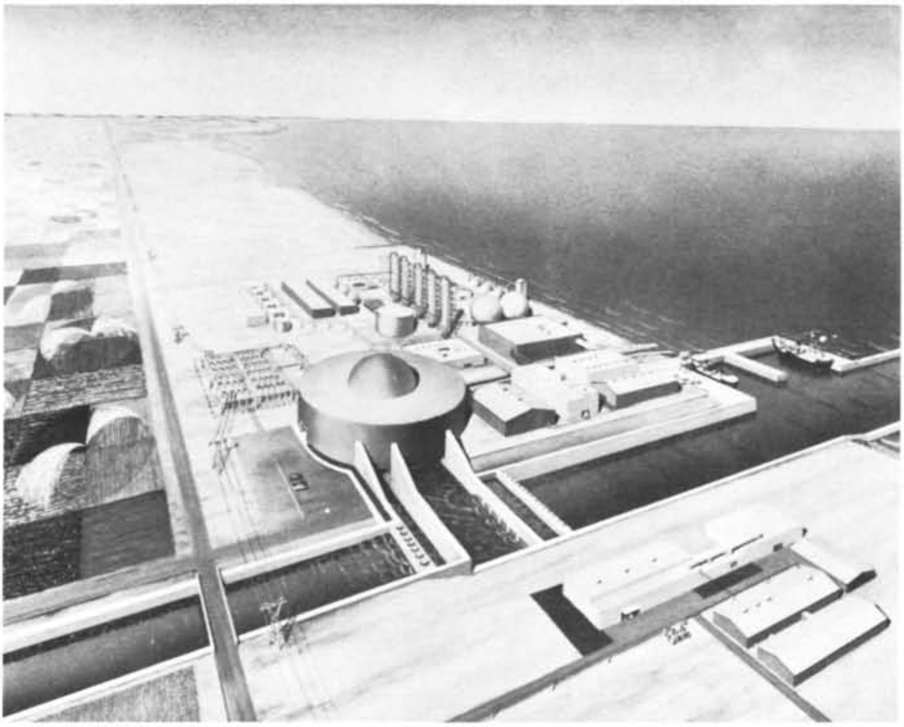
It is for this reason that I consider the achievement of very low-cost energy through the advanced breeder reactor a matter of the highest urgency. It is not merely that with the advanced breeder reactor we shall have a practically infinite source of energy, nor that we believe it will be marginally cheaper than the non-breeder. It is rather that, because of the aforementioned elasticity of demand for electrical energy, the very cheap nuclear energy could become the basis for a new kind of industrial development in which energy-intensive processes replace raw material-intensive processes.

I would go further. The problem of any breeder, let alone an advanced breeder, seem to us so formidable as we view them from our present perspective that I sometimes believe we have allowed our goals to become too modest. The original incentive for developing the breeder was to forestall the inevitable rise in the cost of nuclear power that will occur when and if we run out of low-grade uranium ore. In a sense this incentive is analogous to the original incentive for the development of nuclear power itself — to forestall a rise in the cost of energy from fossil fuels as we run out of the latter.

But the main burden of my argument is that this goal, important as it is, is not enough. To achieve breeders that will compete with burners is a worthy objective. But if the nuclear energy community stops there, it will be missing this new dimension in nuclear energy that the studies of the nuclear powered agro-industrial complex have brought into focus.

I repeat: *the full promise of nuclear energy will be achieved only when we have learned how to generate electricity from nuclear reactors at such low costs that a sizeable fraction, or perhaps the majority, of heavy chemical industry will be based on extremely cheap energy as its ultimate raw material.*

It is difficult to say how cheap energy will have to be to make this profound difference in the way we conduct and organize our industrial economy. It appears that, with energy going for 1.5 mills per kwh, the effect is very important; at 1 mill/kw, the effect may be revolutionary.



Artist's impression of a nuclear powered agro-industrial complex.

Is electric energy from breeder reactors at 1 to 1.5 mills/kwh a credible goal? Most responsible authorities tend to dismiss this as an impossible speculation. Yet the American nuclear economist, J.A. Lane, has recently given arguments that make such a goal less implausible.

Lane points out in the first place that, if the installed electrical capacity increases ten-fold by 2020 (as was projected in the 1962 report to the President of the USA, "Civilian Nuclear Power") , then the unit size of reactors might also be expected to increase — to 5000 Mwe or even 10,000 Mwe. At this size, since the installation is so dominated by the external heat exchange system, it is likely that differences in capital costs between various reactors will be very small. Lane then estimates that the cost of nuclear steam boilers in this size range might be as little as $12 to $24 per kwe; the unit costs of turbogenerators would also be expected to decrease, with increased size and possibly higher frequency, perhaps to $25 to $30/kwe, making a total per installed kilowatt of between $40 and $55. Thus even at 12% fixed charges and 80% load factor, the capital charges could conceivably be as low as 0.7 to 1.0 mill per kwh.

As for the fuel cycle, Lane estimates that, with very large installations of the sort here contemplated, the overall fuel cycle in an advanced breeder might cost as little as 0.1 to 0.2 mill/kwh. These low costs ought to hold for either the fast breeder, based on uranium creating plutonium-239, or the molten salt thermal breeder, based on thorium creating uranium-233. In the former case, the sale of bred material would offset the high inventory charges; in the latter, the sale of bred material may not quite balance the inventory, but, the inventory being small to begin with, this is relatively unimportant. Lane adds 0.2 mill/kwh for operating and maintenance costs and liability in these very large stations to give a total power cost of between 1.0 to 1.4 mills/kwh.

How seriously should one take such estimates? From what I have said, I believe that we must at least examine them seriously. If there is any conceivable possibility of achieving such costs, their achievement ought to be made a major goal of the nuclear energy enterprise.

And indeed, from the standpoint of the integrated agro-industrial complex, some of the requirements for achieving truly low-cost power may be closer at hand than Lane imagines. The complexes we have studied produce 2500 Mwe; complexes producing two to four times as much electricity are not so hard to imagine, especially if, with the energy demand being so elastic, many additional industrial processes were attached to the complex.

Moreover, if the energy is used in an industrial complex, it is highly desirable to produce it continuously: load factors of 95% or more would be aimed at, and this would reduce the capital charges by perhaps 0.15 mill/kwh. But this means that we must achieve an even higher order of reliability in advanced breeder reactors than we have achieved thus far in the light water reactors.

THE JOBS OF THE NUCLEAR ENTERPRISE

What, then, remains to be done in nuclear energy? I have already given part of my answer: the development of the advanced breeder reactor, not merely as an energy system competitive with other energy systems, but as an energy system that will provide power at costs of less than 1.5 mills per kwh, ubiquitously and essentially forever. The incentive to achieve this goal derives from the many industrial processes that we believe will convert to electricity as their primary raw material once such prices are achieved. But this suggests that the nuclear energy enterprise itself — the world's nuclear laboratories and reactor manufacturers and atomic agencies — ought to become much more involved in the development of new and possibly revolutionary industrial uses of cheap nuclear power. The situation is rather circular: there will be relatively little incentive to reduce the cost of energy, even to zero, if only those processes now based on energy are thereby improved; on the other hand there will be little incentive to examine new ways of performing energy-intensive processes unless really cheap energy at some finite time is a credible goal. Thus I would hope the nuclear energy enterprise could shift an increasing fraction of

Dr. Alvin M. Weinberg delivering his lecture.

its effort toward developing energy-intensive processes, particularly in heavy chemical technology. There is already a precedent for this kind of redeployment in the development by nuclear laboratories of new ways of desalting, an energy-intensive process par excellence. I believe this redeployment has already been successful. I should think the nuclear laboratories, in conjunction with the appropriate established industries, ought to look seriously at other energy-intensive processes: like large-scale production of electrolytic hydrogen; or reduction of iron and other ores with hydrogen; or conversion of coal into liquid fuel with electrolytic hydrogen; or possibly even the production of protein, which in some versions is fairly energy-intensive — to mention just a few, rather obvious possibilities. Our experience in such partial redeployment at Oak Ridge has emphasized the great importance of doing at least some of the work concerned with applications of cheap nuclear energy in conjunction with development of better methods for producing nuclear energy: each effort interacts with and gives focus and point to the other.

NUCLEAR ENERGY AS AN INSTRUMENT OF WORLD PREACE

Since this is an international organization dedicated in the broadest way to the aim of world peace, I hope you will excuse me for speculating on the ultimate world impact that these new vistas for nuclear energy might have. We are familiar with vast agro-industrial complexes that have sprung up in various parts of the world to exploit certain natural resources — for example, the huge

SASOL complex in South Africa that is based on extremely cheap coal; or the great aluminium complex in Kitimat, Canada, that is based on water power; or, for that matter, the original Tennessee Valley Authority regional development, again based on natural water. The nuclear power complex possesses many of the same elements as these, but of course has one overriding advantage; it can be placed, by and large, where it makes the most economic or political sense, rather than where the accidents of natural resources and geography dictate. For this reason the complex could become a potent instrument of international development. It takes little imagination to see how a viable complex producing water for agriculture and industrial products could create an entirely different political atmosphere in the Middle East; or how the development of India, with its hungry masses, could be affected by a properly located series of complexes.

But in the long run we return always to the prime question: the development of the advanced breeder reactor that will produce really cheap and reliable power and upon which the ultimate edifice is based. We cannot solve today's social problems with tomorrow's technology. To be sure, present reactors can power agro-industrial complexes in the near future with surprising effectiveness. But we could do much more if we developed the very much cheaper energy source. We must therefore get on with this main business as urgently as our budgets and our energies allow. Mankind will still have massive social problems 10, 20, 30 years from now. One can only hope that, by mobilizing sharply and urgently now, we can create these technologies soon enough so that, as the very least, we shall have tomorrow's technologies to help solve tomorrow's social problems.