NUCLEAR ENERGY AT THE TURNING POINT

Alvin M. Weinberg

This report is based on work performed under Contract EY-76-05-0033 between the U.S. Energy Research and Development Administration and Oak Ridge Associated Universities.

ORAU/IEA(O)-77-19
Occasional Paper
July 1977

DISCLAIMER

CONTENTS

ABSTRACT

In deciding the future course of nuclear energy, it is necessary to re-examine man's long-term energy options, in particular solar energy and the breeder reactor. Both systems pose difficulties: energy from the sun is likely to be expensive as well as limited, whereas a massive world-wide deployment of nuclear breeders will create problems of safety and of proliferation. Nuclear energy's long-term success depends on resolving both of these problems. Collocation of nuclear facilities with a system of resident inspectors are measures that ought to help increase the proliferation-resistance as well as the safety of a large-scale, long-term nuclear system based on breeders. In such a long-term system a strengthened International Atomic Energy Agency (IAEA) is viewed as playing a central role.

NUCLEAR ENERGY AT THE TURNING POINT*

Six years ago at the Fourth International Conference on the Peaceful Uses of Atomic Energy I presented a paper with Dr. Philip Hammond that opened with the following words:

"We in the peaceful nuclear energy community have been comfortable in the belief that what we have wrought over the past 30 years has been an unmitigated blessing for mankind. It comes as a disconcerting shock therefore to find that, just when nuclear energy has achieved such great success, our effort is being challenged on the most fundamental grounds. Where we claim nuclear energy is clean, safe, and necessary, critical voices, particularly in the United States claim it is unclean, unsafe, unnecessary.

"We have always conceded that, in opting for nuclear energy, mankind is assuming a certain risk. Nuclear energy is potentially more dangerous than other forms of energy. It is only by scrupulous attention to detail, and exertion of great care, that we can expect to maintain the safety of nuclear power. So far we have been highly successful.

"Yet there is a much more difficult and profound issue. We are still at the very beginning of the nuclear age. As we think about the possibilities and dangers of nuclear power, we tend inevitably to think

*For presentation before the International Atomic Energy Agency International Conference on Nuclear Power and its Fuel Cycle, Salzburg, Austria, May 5, 1977.

of nuclear power as an isolated, smallish thing. But in the very long run, nuclear energy will almost surely be the dominant energy source. At that time, will we have to confront entirely new questions of environmental impact, questions that could conceivably compromise the whole path we are now taking?"[1]

These words, uttered a half-dozen years ago, have become distressingly relevant today. Our enterprise is not merely on the defensive: in some quarters it is in danger of extinction. In particular, the moratorium on fuel reprocessing in the United States inevitably questions the basic course most of the nuclear enterprise has been following for the past generation.

It will be my purpose first to re-examine why our enterprise is in retreat in so many places; then to ask, "Can we do without uranium?", and finally to propose paths and actions that I believe we shall have to take to achieve an acceptable nuclear future.

Why is Nuclear Energy in Retreat?

We are beleaguered for many reasons. First, many of us were too euphoric in our expectations of nuclear energy. Many are the times I would like to unsay the words I expressed at the tenth anniversary of IAEA in Vienna a decade ago. At that time, with Oyster Creek being contracted at a little over $100 per kilowatt of electricity [kW(e)], it seemed plausible to expect nuclear energy to be extremely cheap, as well as inexhaustible. Our dreams of nuclear-powered agro-industrial complexes seemed like legitimate extrapolations from what we thought was demonstrated technology. That the technology turned out to be much more expensive for reasons that few could foresee, or that other sources of energy have also become very expensive, is beside the point: disillusionment with our predictions made it difficult for the nuclear community to retain the confidence of some of the public. Yet I am unprepared to give up: reactors with an intrinsically low fuel-cycle cost, such as CANDU-Th or molten salt, may yet be realized.

Second, despite the escalation of cost, nuclear energy in the past half-dozen years has become immensely important — more important, say, than the three wise men of Euratom predicted in the middle 1950s. Their goal of 15,000 megawatts of electricity [MW(e)] in Western Europe by the late 1960s has long been passed. But in becoming important, nuclear energy has intruded on the public consciousness. Basic concerns about massive radioactivity, which after all is a new thing on earth, have become widespread simply because nuclear energy itself is widespread. Moreover, I do not believe we in the community have really anticipated the systems problems of a fully deployed nuclear economy. We did not take fully seriously the possibility that nuclear energy would be as successful as it has become. Thus we did not clearly plan how to expand uranium supply or enrichment capacity or all the details of the waste management system to meet the demands of a totally deployed nuclear energy enterprise. We expected these to happen rather automatically in response to market forces, or as in the case of waste disposal, to be deferrable.

Third, we are entering the maturity of nuclear energy at the same time the world has discovered the environment. It may have been naive of us to believe that because a properly operating nuclear system is far less polluting than is a coal-burning power plant that we could permanently win over the environmental movement to the banner of nuclear energy. But with our present means of rapid communication, doubts and concerns — of which some are legitimate, some are not — easily escalate. Though nuclear moratoria legislation and initiatives in the United States have all been defeated by approximately a 2 to 1 margin, a consensus with respect to the underlying desirability of nuclear energy in many countries no longer exists. In the absence of consensus the nuclear regulatory process is subverted: licensing a reactor becomes a battle in what one U.S. Nuclear Regulatory commissioner has called a "religious war".

All of this is played against the threat of proliferation — and this concern, which to some is viewed as the overriding objection to nuclear energy, has in the past year affected the course of nuclear development more drastically than any other single factor. The recent decisions in the United States, both with respect to recycle and the Clinch River Breeder, were made in good measure because of concern over proliferation. Proliferation has become a sort of ultimate Sword of Damocles that hangs over nuclear energy.

Can We Do Without Uranium?

Faced with these and other objections to the very validity of our enterprise, I think it is necessary for us to confront once again the original question, Can we do without uranium? The answer must of course be yes: civilization would not perish had fission not been discovered. After all, there was nothing foreordained about the discovery of fission in 1938 or about η, the number of neutrons produced per neutron absorbed, being greater than unity. Had η been less than 1, a chain reaction would have been impossible; and had η been less than 2, a breeder would be impossible. That God happened to legislate η (^{239}Pu) = 2.8 for fast neutrons, and that man was lucky enough in 1938 to discover fission, which in a way is an oddity rather than a central thread in nuclear science, must be regarded as a bit accidental. And before 1938, those who speculated on man's future were prepared to contemplate a world that knew no nuclear energy: when the fossil fuels ran out, it was generally expected that we would turn to the sun — either directly, or perhaps in the form of biomass, or wind (Palmer Putnam's big windmill at Grandpa's Knob in Vermont was completed in the early 1940s), or ocean thermal gradients (Claude's experiments in the 1920s and 1930s); and some geothermal energy. So a fission-free world was the only world until 1938, and somehow our society seemed resigned to getting along without fission.

And in the very short run, for countries well-endowed with coal, fission, to a degree, can be replaced by coal. At the Institute for

Energy Analysis we have examined the consequences of a nuclear moratorium in the United States beginning in 1985 and lasting until 2010.[2] Our main conclusion, which followed largely from our projection of a relatively low rate of energy growth in the United States, was that in principle we could largely substitute coal for additional uranium beyond what we now use over this period — but that the pressure on coal would be very heavy, possibly intolerable: we would have to face the possibility of digging some 5×10^9 tons of coal per year — about 8 times our present coal production. But this analysis is of little relevance for the large parts of the world that possess no coal or oil — for them an alternative to fossil fuel is a necessity even in the relatively short run.

The dreamers of the pre-fission era, particularly H. G. Wells, were aware that an inexhaustible, cheap source of energy was eventually necessary — if not for the survival of the race, then to set the world free from Malthusian Catastrophe. And Wells' simple message, later reiterated by Sir Charles Darwin in his The Next Million Years — that eventually man's fate depends on the energy at his disposal — remains as true today as when he first delivered it some 60 years ago.

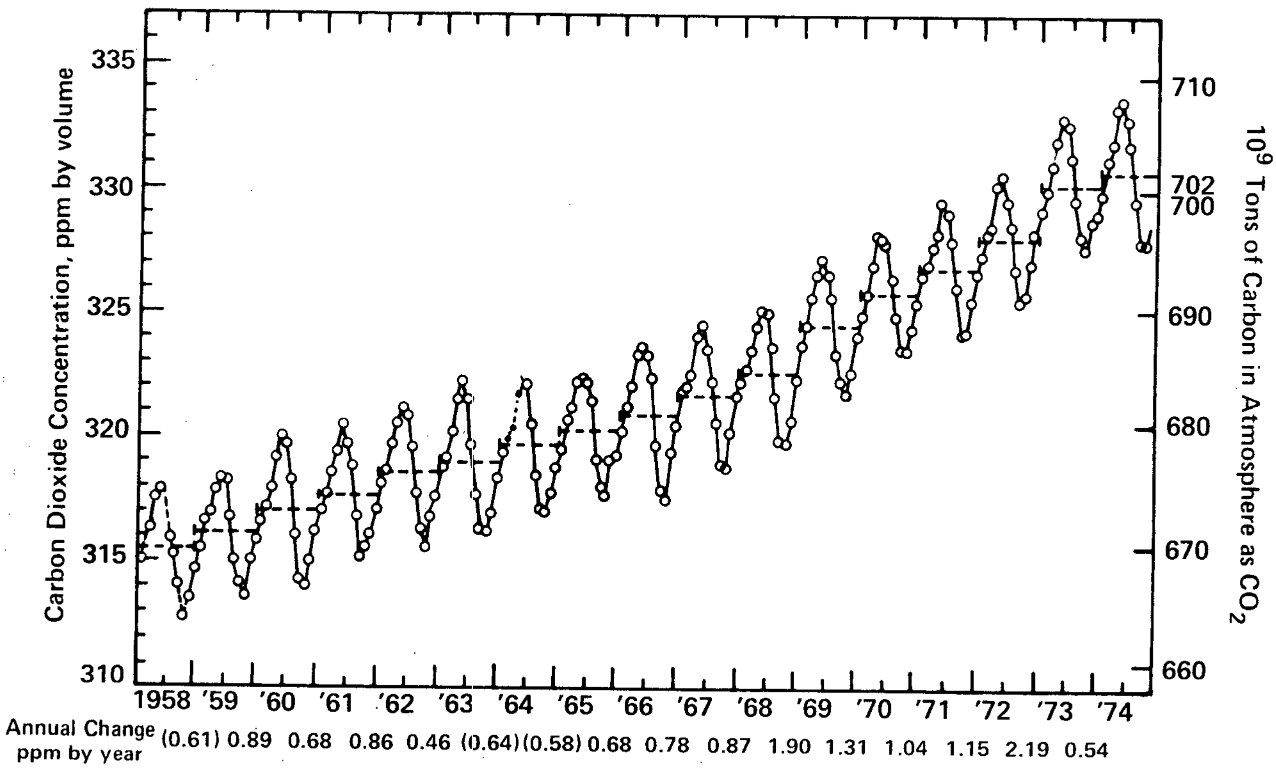
Let us then examine what a world without uranium might look like; but more than that, a world without fossil fuel as well. We must contemplate this latter eventuality, bizarre as it seems, on two accounts: first, our fossil reserve though very large, is finite; but second, and possibly more important, we may have to limit our burning of fossil fuel because of a possible CO_2 catastrophe.

The atmosphere contains about 700 x 10^9 tons of carbon in the form of CO_2. The concentration of CO_2 in the atmosphere has been increasing at the rate of about 0.8 parts per million (ppm) each year; it has risen from about 315 ppm to 330 ppm in the 19 years since Keeling began to monitor CO_2 in 1958 (Figure 1).[3] Though there is still some doubt on this score, the evidence strongly suggests that the increased CO_2 comes from the burning of fossil fuel rather than from clearing of forests. About one-half the CO_2 injected into the atmosphere from burnt fuel remains there. Thus if the estimated total world coal resource of 10 x 10^{12} tons eventually is burned, and one-half remains in the atmosphere, the CO_2 concentration might increase about eightfold. If only the reserve base is burned (the reserve base being defined as the amount recoverable at about present cost with present-day techniques), the CO_2 concentration would more than double.

When this might happen no one knows. Many guesses as to the world's ultimate energy demand have been made in recent years; one of the best known is that of F. Niehaus, who projects by 2050 an asymptotic world producing energy at a rate of nine times the present — about 2,000 quads per year compared to the present 220 quads per year.[4] R. Rotty at the Institute for Energy Analysis estimated the world's energy demand separately for developed and developing countries. He arrives at a total demand of 1,200 quads by the year 2025; the bulk of the expansion comes from the less developed countries since, Rotty argues, these countries use so little energy per capita now they are likely to increase both their per capita use of energy and their total population relatively

FIGURE 1

ATMOSPHERIC CARBON DIOXIDE CONCENTRATION AT MAUNA LOA OBSERVATORY
(1958-71 data from Keeling et al., 1976; 1972-74 data from Keeling, private communication)



faster than the developed countries. Rotty's projections are in fair agreement with those presented at the November 1976 joint meeting of the American and European Nuclear Societies by Andre Giraud of France. Though Rotty's scenario still allocates but 50×10^6 kilojoules per person per year in the third world — only one-fifth that used in the developed countries — the total relative contribution to energy demand from the developing world increases from less than 20 percent to more than half by 2025. Before accepting this scenario I must concede that some economists, particularly Professor Houthaker, claim that price alone will prevent the world's energy demand exceeding 500 quads by 2025. Nevertheless I believe it is prudent to assume that the third world will not forever be content with a per capita energy expenditure one-tenth or one-twentieth that of the developed world.

Let us then examine the consequences of Niehaus' scenario — 2,000 quads by 2050. If the bulk of this energy is supplied by fossil fuel, the CO_2 concentration may double by about 2025. Unfortunately we cannot say with certainty what the effect on climate of this increase will be: H. Flohn of Bonn suggests a 300-500 kilometer shift poleward of the climatic zones. Manabe and Wetherald, using a global circulation model, predict that a doubled CO_2 concentration will increase the overall average global temperature by 1-3°C, the pole temperature by 8°C. Such a strong shift would almost surely change the world's climatic zones in an unprecedented way, with economic consequences and effects on agriculture that no one can foresee. Let me hasten to point out that Manabe and Wetherald's model is incomplete — in particular it does not include cloud feedback, nor does it adequately treat the sea-air interface. And indeed, the effect of CO_2 may be in a basic sense unpredictable — we may have to allow the climate itself to tell us how it will react to a doubled CO_2 concentration. But the point is that, far-fetched as it may seem to some, CO_2 may be another Sword of Damocles that hangs over our industrial society, and that may end the fossil fuel era much sooner than would be expected simply from depletion of coal. Above all it injects a somber note of uncertainty into our energy future, one that we ignore at our peril.

I believe it is time for our political people to recognize this possibility. I do not believe it premature for the appropriate United Nations agency to form a group of international experts who can better define the CO_2 problem, assess global and national consequences, and propose credible responses.

Asymptotic Energy Scenarios

Let us then consider how man might provide 2,000 quads of energy annually after he has used his fossil fuel, or has decided to husband it for petrochemicals, or must proscribe its use because of the CO_2 catastrophe. I shall examine two possibilities: one based primarily on the sun and other renewable resources; and a second based on nuclear energy. To do this properly we should analyze each end use and estimate how much energy is used as low-temperature heat, high-temperature heat, electricity, and mechanical work (largely transport). This I have not done and my speculations can be faulted in this respect. Instead I have simply assumed that 25 percent, or 500 quads, goes for space and water heating, and that at least 50 percent or 1,000 quads goes through electricity. The remaining 500 quads — largely comprising transport — I shall assume are provided either by electricity, or by some renewable source that can substitute for petrol. This breakdown is close to the one many analysts project for the United States by the turn of the century.

The Sun and Other Renewable Sources

How could we meet this budget with renewable sources? Aside from the sun, geothermal energy seems to be the largest such source. Yet the steady state geothermal gradient on land is only 200 quads per year, and most of this is unusable for generating electricity — we might count on perhaps 10 quads of heat and 2×10^{12} kilowatt-hours of electricity [kWh(e)]. Hydro, wind, waves, and tides can hardly add more than 12×10^{12} kWh(e). Thus, at the energy demand we project, these sources can hardly make a dent on the requirement placed on the sun.

What then would be involved in deriving from the sun perhaps 500 quads for space and water heating, 500 quads for transport and some high-temperature heat, and 1,000 quads as electricity? The 500 quads for space and water heating seems easiest: I shall assume all of this can be provided directly by the sun, though this certainly will require many changes in the way we build our houses.

The 500 quads for transport and some high-temperature heat we shall provide with biomass since the use of biomass does not add to the net

CO_2 burden in the atmosphere. Now if we assume a photosynthetic efficiency of 0.6 percent — which is 5 times the global average of 0.13 percent, then to get 500 quads from biomass would require about 13×10^6 km^2 of land — about 10 percent of the earth's land area. When one considers that in this asymptotic state much land will be needed for growing food, one-tenth of the world's land area devoted to growing biomass for energy seems excessive. (Conceivably this could be reduced if practical photosynthetic yields, say 5 times larger, could be achieved.) But this is surely an advance that we have no right to assume will come to pass. One can hardly escape the impression that biomass on so large a scale is barely practical.

I would say the same for solar electricity _if it is the primary source of energy_. It is not that the required land area is impossibly large: at 18 percent conversion efficiency, with either power towers or photovoltaics, we can get 300 kWh(e) per m^2 per year from the sun. Thus to supply 100×10^{12} kWh(e) annually would require 3×10^5 km^2, which is very large but not impossible. (Note that electricity can be produced directly from the sun with photovoltaics some 100 times as efficiently as it can be produced from biomass burned in a power plant.)

The main problem, of course, is storage. Ordinarily we think of a solar electric system as a supplement to a firmly based fossil- or nuclear-fueled electrical system. In that event the system does not require storage for more than, say, about 12 hours. But if the solar electric system truly stands alone, then it must store enough electricity to tide one over protracted periods of cloudiness — say 6 to 12 days per year. Storage of electricity is expensive: say \$40 per kWh(e). And if we require six days' storage, then the capital cost of a stand-alone solar electric system would be 100¢ per annual kWh(e) — some 3 times as much as the capital cost of an incremental system that required no storage. This is to be compared with a fossil or nuclear plant which at \$1,500 per kW(e) would cost about 25¢ per annual kWh(e). Even taking into account the cost of the fuel cycle — say 5 mills per kWh(e) — it seems that electricity from a stand-alone solar system will be several times — perhaps as much as 4-6 times — as expensive as electricity from nuclear sources.

Am I being fair to the sun in making this judgment? Obviously improvements will be forthcoming — for example, cogeneration, or better collectors, possibly even ocean thermal energy conversion (OTEC) which, because it requires no storage, deserves much more serious attention than it has received thus far. But these are hopes, not realities. Our general experience has been that untried energy systems cost more, not less, in practice than in theory. I conclude that an all-solar world would be possible, but could not provide as much as 2,000 quads, or would require the world to pay much more for a unit of energy than it now pays, or both. Thus an all-solar world would be very different from our present world; in embracing such a world, as some would have us do, we would quite likely be moving along social paths whose risks simply cannot be assessed.

An Ultimate Future Based on Breeders

What would be involved in meeting our projected energy demand with breeders? Rather than assume the entire 2,000 quads is provided by nuclear sources, I shall again assume that space and water heating, amounting to 500 quads, is provided by the sun. There then remains some 1,500 quads (less the small amount provided by geothermal and other renewable resources) to take care of industrial heat, transport, and electricity. For simplicity we shall assume that all these demands can be provided electrically: industrial heat with high-temperature heat pumps, transport by batteries or other electric drive.

An asymptotic energy system generating 1,500 quads per year — which is converted into 150 x 10^{12} kWh(e) — would require 25 thousand 1,000-MW(e) reactors — or, since the unit size historically has been maintained as a fixed fraction of the total electrical system, say 5,000 reactors each of 5,000 MW(e). Is such an energy system based on breeders plausible?

The readily calculable constraints such as uranium requirement, global heat load, and land committed to waste disposal do not appear to be limiting. The global heat load, about 1,500 quads, is only one-tenth the equivalent heat load caused by a doubling of CO_2 concentration. The system would require about 30,000 tons of uranium per year — which to be sure would mean burning the residual uranium and thorium in the rocks or extracting uranium from the sea. And the burial of high-level wastes, at 0.6 hectares per reactor per year, would preempt 25 km^2 each year —

after 1,000 years 25,000 km^2 will have been used, but by that time the radioactivity would have decayed sufficiently to permit layering of new wastes above the old. But altogether these do not seem to me to pose insuperable difficulties.

It is the malfunctioning of the system, particularly the possibility of accident and traffic in plutonium, that gives one pause. We do not have estimates of meltdowns in breeders comparable to Rasmussen's estimate of 0.5×10^{-4} per year for a meltdown releasing appreciable radioactivity in a light water reactor. If we assume the same probability for the breeders in our asymptotic system, then for 5,000 reactors the a priori expected meltdown rate would be 0.25 per year — i.e., one such accident every four years.

To be sure, the majority of these meltdowns would cause little off-site damage. Nevertheless, it remains to be seen whether a reactor accident every four years will be tolerable. My own instinct is that in the present climate the answer would be no; but in the future I believe it is fair to assume first that the accident probability will be reduced much below Rasmussen's 0.5×10^{-4}, and second, that the public will eventually accept radiation as a part of life's hazards rather than view it as something mysterious and special.

The total plutonium in the system amounts to 125,000 tons and at a burn-up of 100,000 megawatt-days per ton, about 30,000 tons of plutonium is reprocessed each year. This amounts to about 100 tons per day that must be accounted for — a staggering amount.

These oversimplified estimates reinforce the view Dr. Hammond and I expressed six years ago — that the price nuclear energy demands, if it indeed becomes the dominant energy system, may be an attention to detail, and a dedication of the nuclear cadre, that go much beyond what most other technologies demand. I realize that many in our nuclear community would deny these assertions: but I would insist that we are unaccustomed, perhaps unwilling, to project our technology as far as I have — unwilling in a sense, to face up to the consequences of complete success. When one does, one cannot avoid recognition of the social problems posed by our technology.

Can We Construct an Acceptable Nuclear Future?

I put the previous scenarios forward with much diffidence, especially since events proved me so poor a prophet when in Vienna ten years ago I estimated nuclear energy would be 10 times less expensive than it has turned out to be. And indeed, there are many possibilities that could change things drastically: the world may never require 2,000 quads, either because population levels off, or because the disparity in energy demand between rich and poor will somehow be maintained; or fusion may work and be cheaper than breeders, or possibly one of the electrical breeder schemes will be feasible; or solar energy may eventually turn out to be much cheaper than any of us can here imagine, but using means and mechanisms that none can here imagine, either. But this much seems clear: that if the world foreswears nuclear energy, from what we now know of solar energy the world would have to adjust permanently either to much more expensive energy than we now enjoy, or much less energy than the developed countries use, or both. In this somewhat limited sense we can hardly do without uranium.

And of course, the future energy system is unlikely to be based exclusively on nuclear reactors or exclusively on renewable resources: it will be a mixture. Actually, in my nuclear scenario, I still assign space and water heating, amounting to 25 percent of the total energy, to the sun; I would guess that biomass will be used much more widely, and wind and geothermal will be exploited to the full, as may OTEC. But these will not change the problem qualitatively. Unless fusion works we shall still have to contemplate a world that ultimately depends on many thousands of nuclear reactors. And even in a world using only 500 quads with 375 quads coming from nuclear reactors, each one now being only of 1,300 MW(e) capacity, we would still have some 5,000 breeders.

Such a world is not a simple one. A world-wide meltdown rate of 0.25 per year may well be unacceptable; and if one is worried about proliferation now, how can we seriously contemplate a world in which as much as 100 tons of plutonium may be reprocessed every day? It appears to me then that the future of our enterprise depends somehow on our devising a nuclear energy system, i.e., the reactors and supporting facilities, their siting, and their institutional matrix, that confronts these contingencies — meltdown and proliferation — fully and unflinchingly and with the realization that the system we devise must last for a very long time. To do this we must try to visualize the systems difficulties, possibly even exaggerating them by presenting scenarios which some may consider impossibly expansive. Can we then conceive of fixes, both technical and institutional, that would allow us to have nuclear energy under conditions that the future will find acceptable? What might be some of the characteristics of such fixes?

As for reducing the a priori probability of an uncontained meltdown, I believe this we will gradually achieve. The Rasmussen study identified specific weaknesses that contribute most significantly to the 5×10^{-5} per year meltdown rate. As Smidt and Salvatori pointed out at the 1976 Washington ANS-ENS meeting, failure of two check valves in a small pipe contributed significantly to this probability. Having pinpointed the weakness, it should in principle be possible to correct it. And I believe it is quite likely that the Rasmussen probability can and indeed will be well below 5×10^{-5} per year. But having done all we can technically, we must still rationalize the institutional structures of nuclear energy for the long term.

A fully developed nuclear system will almost surely have to be one that commits only certain pieces of land to radioactive operations. These pieces of land will have to be dedicated into perpetuity in much the same way that certain lands in the United States are committed into perpetuity for use as national parks or in the same way that Johnston Island in the Pacific was committed to testing. These sites would have to be chosen to accommodate the characteristics of nuclear reactors rather than of the existing electrical grid. Moreover, I continue to believe that a large degree of collocation of reactor and recycling facilities is desirable. I simply cannot imagine a nuclear energy system as large as the one I project, or for that matter even one-fifth as large, is credible unless traffic in fissile material and radioactivity is kept to a minimum. Collocation of reactors and reprocessing plants helps to achieve this.

As we begin to deploy breeders we ought to site them, insofar as possible, along these lines in the full realization that we may be committing ourselves to a siting policy that will prevail for an immensely long time.

The siting policy I espouse — relatively few numbers of very large sites — may be evolving inevitably. As it becomes more and more difficult to find new sites, the existing sites will expand. In the Soviet Union sites for 10×10^3 MW(e) are planned, and in Canada such siting policy seems to prevail. We at the Institute for Energy Analysis have found that some 80 of the 100 existing U.S. sites are well located with respect to cooling water, low local population, and high future power demand, and could be expanded to a capacity of 20,000 MW(e). We also estimate that the entire asymptotic nuclear enterprise in the United States could be managed with a commitment of no more than 13,000 km^2. This would be reduced if ocean siting were used; and I believe ocean siting will be necessary in some parts of the world.

Siting alone is insufficient. In addition, security standards will have to be strengthened -- which is easier if collocation is adopted generally. But perhaps most important is the strength of the corps that deals with nuclear energy: Our technology is different, and we would do well to admit this instead of denying it. Fifteen billion curies of radioactivity in a 1,000 MW(e) pressurized water reactor is something very special indeed, and the training and professionalism required of those who handle nuclear energy is and always will be extremely high.

And a good part of the justification for large collocated sites comes from the strength of the cadre that inevitably develops in such centers: such cadres were developed at the U.S. sites — Oak Ridge, Hanford, Savannah River, Idaho Falls. If in final analysis the safety of the nuclear system depends on the strength of those who man the system, I would insist that we enhance the strength of the nuclear corps by centralized siting, and thereby improve the safety of the system.

Breeders and Proliferation: The Ultimate Question

The future is uncertain: no one can say that the measures I suggest — collocation of breeders in dedicated sites, added security, strengthening of the nuclear corps — will be sufficient to restore confidence in nuclear energy among those who have lost that confidence. I hope it will. On the other hand, the path that seems to be taken in some quarters — which is a rejection or at least deferral of the breeder — appears to me to add to our uncertainty, not diminish it. Breeders, when first discussed 35 years ago at Chicago, were viewed as the ultimate aim of nuclear energy. But when they would be needed puzzled us then because we knew neither future energy demand nor uranium resources. We still know none of these with certainty — and it is these uncertainties that the breeder eliminates. This has always been a prime argument for early introduction of the breeder. Though our good friend Bennett Lewis has often argued that breeders are not necessary, I believe even he would concede that if breeders work and become practical, then they simplify the nuclear system — they trade off complexity in the fuel cycle for the greater complexity and uncertainty in procurement and enrichment of uranium. Most of us figured this was a good exchange, though not all believe the Liquid Metal Fast Breeder Reactor is the sole direction for breeder development. Moreover, the idea that breeders confer a measure of energy autarky always seemed attractive to some of us.

We are now in the throes of full confrontation with the threat of proliferation posed by the breeder. All in the nuclear community know that the breeder is by no means necessary for proliferation — that there are more direct routes such as dedicated reactors and centrifuges. Proliferation is therefore in large measure a political issue that fundamentally must be dealt with politically.

Yet I think the technical community must not dismiss the matter so easily. We do have a serious responsibility to devise those breeder technologies or systems that minimize the possibility of diversion. We cannot solve the proliferation problem; but can we not at least separate proliferation from power production?

I cannot pretend to have clear answers. After all, reactors and reactor systems have not in the past been designed to be proliferation- or diversion-proof. And, just as some reactors may have a lower a priori meltdown probability than others, I suppose some reactors and reactor systems may be more diversion-proof than others. Exploration of such possibilities we ought to accept as a challenge.

But this much seems clear to me — that a collocated, centralized siting system has the possibility of incorporating barriers to diversion that are less easy to visualize in a more dispersed system. Is it unreasonable to imagine that in a fully developed center there will be full-time, permanent IAEA inspectors who can know intimately and in detail exactly what is going on at their site and who can set into motion the appropriate actions, including notification of the Security Council, should they detect diversion of fissile material? This is the kind of semi-technical invention that I believe is possible and that we shall have to address seriously.

I have called my talk "Nuclear Energy at the Turning Point"; it is being given on the 20th anniversary of the International Atomic Energy Agency. Our enterprise is at a turning point in large measure because the issue of proliferation — the same issue that bedeviled the world 30 years ago and gave rise to ideas for total internationalization of the atom such as the Acheson-Lilienthal plan — has once more assumed such large proportion. It may well be that in some sense the world can live comfortably with nuclear energy only by reinventing some version of the

Acheson-Lilienthal plan. Have we not taken a first step in that direction with the establishment of the International Atomic Energy Agency and the Non-Proliferation Treaty? I suspect that whether nuclear energy itself will prosper in ways we have always dreamt or will always be a source of contention and concern because we cannot deal with proliferation — that this in a practical sense will depend on how effectively IAEA can fulfill, and indeed, expand its mission. It will take imagination, it will take courage, it will take luck. The future may well depend on how successfully we can respond to the political, even more than the technical, challenge posed at this turning point in nuclear energy.

REFERENCES

1. A. M. Weinberg and R. P. Hammond (1972). "Global Effects of Increased Use of Energy", in Peaceful Uses of Atomic Energy (A/CONF. 49/P/033), proceedings of the Fourth International Conference in Geneva, September 7, 1971, International Atomic Energy Agency, Vienna, Austria.

2. C. E. Whittle et al. (1976). "Economic and Environmental Implications of a U.S. Nuclear Moratorium, 1985-2010", ORAU/IEA-76-4, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, September.

3. C. D. Keeling et al. (1976). "Atmospheric Carbon Dioxide Variations at Mauna Loa Observatory, Hawaii", *Tellus*, 28(538).

4. F. Niehaus (1976). "A Nonlinear Eight Level Tandem Model to Calculate the Future CO_2 and C-14 Burden to the Atmosphere", Research Memorandum RM-76-35, International Institute for Applied Systems Analysis, Laxenburg, Austria.