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THE SAFETY OF NUCLEAR POWER[1]

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Nuclear power plants and their subsystems have caused less damage to human health and to the environment, per kilowatt-hour, than have fossil-fueled central power stations. Thus Professor Lester B. Lave of Carnegie-Mellon University points out that from mining alone the damage imposed by coal is twelvefold greater, per kilowatt-hour, than is that imposed by nuclear energy. (Professor Lave's argument is based on the fact that some 120,000 coal miners today receive about $300 per month compensation as the result of black lung disease.) C. Starr, M. A. Greenfield, and D. F. Hausknecht writing in Nuclear News, Oct. 1972, have compared the radioactivity hazard from nuclear plants with that from oil- or coal-fired plants. Their results show that to reach air quality standards for oxides of sulfur and nitrogen and radioactivity in Los Angeles County one could tolerate 160,000 nuclear plants of 1,000,000-kilowatt capacity, but only 10 oil-fired or 23 natural-gas plants of this size.

Granted that properly operating nuclear power plants and their subsystems - including mining, transport and chemical reprocessing of used reactor fuel elements, and disposal of radioactive wastes - are benign and have been so demonstrated, are there concerns regarding the possibility that these systems may malfunction and cause hazard to people and

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to the environment? This is a perfectly legitimate question that deserves serious and thoughtful consideration; and it is this aspect of the matter that I shall address.

A properly operating nuclear power plant and its subsystems is and can remain as innocuous a thermal power plant as man has ever devised. The whole safety issue then centers around the possibility that a nuclear plant or its subsystems may malfunction so grossly as to cause damage to the environment or to people.

At the outset, we must remember that the technical community has always recognized that a nuclear system is potentially a dangerous device. For every kilowatt of electrical power generated there will be in equilibrium in the reactor about 10,000 curies of radioactivity, one curie being the radiation equivalent of one gram of radium. The radioactivity is in the form of various fission products, as well as - in the Liquid Metal Fast Breeder Reactor (LMFBR) - about 3.5 grams of Plutonium-239 (new fuel, that produced in the breeder, is itself radioactive). A 1,000,000-kilowatt breeder therefore has in equilibrium about 10 billion curies of fission-product radioactivity as well as about 3500 kilograms of Plutonium-239. Thus we are dealing with highly toxic materials. That, despite these potential dangers, I can assert that nuclear systems per kilowatt-hour have caused much less damage to the biosphere than have other sources of thermal energy, is a tribute to the ingenuity and foresight of the reactor engineer. From the earliest days of nuclear energy we nuclear people have been constantly reminded of this potential danger. (In 1942 one of the first jobs I did for the Manhattan Project was to estimate the hazard caused by minute amounts of radioactive carbon that would be emitted

from the early air-cooled graphite reactors; and General Leslie R. Groves insisted that Enrico Fermi move his West Stands critical reactor from the center of Southside Chicago because of the potential hazard.) Being so sensitively attuned to this potential, we have developed techniques and methods for handling these materials safely. The question is, successful as we have been in the past, what can we say about the likelihood of our continuing success in the future when large nuclear energy reactors will dot the landscape everywhere?

The potential hazard of a nuclear system arises from the toxicity both of the materials that keep the system burning and from the fission-product ashes. Plutonium-239, with a half-life (the time during which one-half of the original material changes by radioactive processes) of 24,400 years, is lethal to man in doses of about 16 thousandths of a gram if ingested in the lungs; Strontium-90, with a half-life of 30 years, will be lethal if about 70 millionths of a gram is ingested. Iodine-131, with a half-life of eight days, will be lethal after ingestion of only about 30 billionths of a gram. Thus the potential hazard lies in the possibility of even small quantities of these materials getting into the biosphere; the countermeasures amount to controlling these materials at every stage of the process to prevent any significant amount from entering the biosphere.

The whole nuclear power system involves four subsystems: (1) mining and refining uranium to fuel the reactor; (2) the reactor itself; (3) transport and chemical processing of radioactive materials from the reactor; and (4) waste disposal. What can one say about the safety of each of these subsystems?

Mining and Refining: There seems to be evidence that uranium miners run a greater risk of lung cancer than does the general public. If the miner smokes, the risk is compounded. Recent studies by F. E. Lundin, J. K. Wagner, and V. E. Archer of the U. S. Public Health Service, suggest that miners who are exposed to 160 working level months (WLM), the presently accepted level (assuming the miner works 40 years at four WLM per year), will have an incidence of lung cancer five times greater than does the general public. If the miner works only 25 years at this level (a total of 100 WLM), it is not clear that there is a statistically significant increase in lung cancer. Nevertheless, the number of deaths caused by mining of uranium, per kilowatt-hour, is much less than those from mining of coal, simply because there are so many fewer miners involved per kilowatt-hour.

Reactor: There are two quite different potential hazards from a nuclear reactor. First there are the routine effluents - including tritium which is a radioactive form of hydrogen, radioactive fission gases from possible leaking fuel elements, radioactive cobalt from corrosion products, etc. Second there is the question of a major, catastrophic accident to a nuclear reactor that might result in an appreciable fraction of the radioactive inventory being released to the environment.

As for the first, the release of small quantities of radioactivity, this matter was the subject of some controversy a few years ago as a result of questioning by John Gofman and Arthur Tamplin at the Lawrence Radiation Laboratory as to the adequacy of the radiation standards then in force. I shall not go into the merits of their argument, but shall simply state that the current standards are now so low - 5% of the amount

we receive from natural sources - at the reactor site boundary as to make the whole issue a non-issue. [By comparison, the added radiation one gets by sleeping adjacent to one's wife whose body (as does everyone's) contains radioactive potassium, is around 7% of the standard for the reactor site boundary. This is a classic case of balancing benefits versus risks!] And indeed, nuclear power plants are now designed to meet these very stringent requirements, and in fact are doing so; here a technological fix has completely resolved a controversy.

The question of the likelihood of a serious accident is less easily disposed of. As I have said, even during the Manhattan Project, we realized that a nuclear reactor could undergo what is known as an excursion - that is, if too many control rods were removed, the reactor power could surge to dangerous levels. This, however, is not the main worry, for such excursions are inherently self-limiting both in time and magnitude. Rather, the worry is that in a very high-powered reactor, immediately after the chain reaction has stopped, the fission products at least momentarily continue to generate 7% as much energy as is generated during fission operation. This "after-heat" decays to about one percent in an hour. Thus a 1,000,000-kilowatt pressurized-water reactor, which is producing, say, three times this amount of heat, will immediately after shutdown continue to produce about 220,000 kilowatts of heat. This decays to 40,000 kilowatts in about an hour, and to 15,000 kilowatts in 24 hours. Thus a high-powered chain reactor <u>must</u> continue to be cooled for a considerable time after shutdown if fuel meltdowns are to be avoided.

It was Edward Teller who some 25 years ago insisted with great prescience that in these respects nuclear reactors were potentially dangerous,

and therefore they should be subjected to the most searching kind of technical scrutiny before they were built. It was on this account that the Advisory Committee on Reactor Safeguards (ACRS) was formed in 1953 with Rogers McCullough as its first chairman; and ACRS has, ever since, been immensely important in establishing norms of engineering practice that would forever prevent the loss-of-coolant or other accident.

The response of the engineer to the knowledge that an uncooled reactor was a dangerous thing went in two directions: the first, and most obvious, was to build a stout, air-tight pressure containment vessel around every reactor; the second, perhaps less obvious, was to provide high-powered reactors with what are called active engineered safety features - various back-up safety systems which would spring into action to make certain that in the event the main cooling system failed there would be ample "fire hoses" available to prevent the reactor core from melting.

Why bother with the back-up cooling systems if the containment vessel in final analysis will catch whatever radioactive debris might be created in an accident and thus prevent harm befalling the public? And indeed this was the attitude in the earliest days: the first containment vessel was a 225-foot diameter sphere around the Sodium Intermediate Reactor (SIR) in Schenectady; it was considered a last-ditch catch-all that in the event everything went wrong in the main system (SIR had no back-up cooling system) the reactor would not create a <u>public</u> hazard.

Two considerations, however, led reactor designers to incorporate active engineered safety features. The lesser is that reactors are valuable devices, and meltdowns, even contained ones, are messy. Thus it gradually became apparent that such features as the emergency core cooling system

(ECCS) were highly desirable, even if the reactor itself were surrounded by a containment shell capable of containing all accidents.

The second consideration, however, is more fundamental and goes like this. As long as reactors were relatively small we could prove by calculation that even if the coolant system and its back-up failed, the molten fuel could not generate enough heat to melt itself through the containment. However, when reactors exceeded a certain size, then it was no longer possible to prove by calculation that an uncooled reactor fuel charge would not melt through its containment vessel. This hypothetical melt-through is referred to as the China Syndrome for obvious reasons. Since we could not prove that a molten fuel puddle wouldn't reach the basement of a power reactor, we also couldn't prove whether it would continue to bore itself deeper into the ground.

Whether or not the China Syndrome is a real possibility is moot. The point is, however, that it is not possible to disprove its existence. Thus, for these very large reactors, it is no longer possible to claim that the containment shell, which for smaller reactors could be relied upon to prevent radioactivity from reaching the public, was sufficient by itself. In consequence, the secondary back-up cooling systems, which originally were designed simply to prevent property loss and awkward clean-up, must now be viewed as the ultimate emergency protection against the China Syndrome and as an integral part of the reactor safety system.

In saying this I omit another deeply essential safety consideration, and that is the extraordinary care that nuclear engineer, designer, constructor, and operator take at every stage to ensure that the initiating malfunctions that could require emergency cooling will never occur. There

are those in the reactor community who believe that the extraordinary attention to what we call quality assurance will always ensure that the back-up cooling systems will never be called into play.

I shall not belabor this point here, but will return to it later. The fact remains that, if one is trying to be practically 100 percent sure of always being able to cope with a reactor meltdown, then one must in this context and with these assumptions (credibility of a loss-of-coolant accident, credibility of the China Syndrome) be absolutely certain that the engineered safety features, particularly the emergency core cooling system, will work as planned.

It was largely this background that led the AEC in late 1971 to promulgate criteria for pressurized-water nuclear reactors that in effect placed an upper limit on the conceivable temperature the reactor might reach following a loss-of-coolant accident. Very arduous and sometimes acrimonious hearings related to these criteria were held last year. During this time every aspect of the operation of the emergency core cooling systems both in pressurized-water reactors and in boiling-water reactors has been thoroughly re-examined. Although they are obviously cumbersome, the hearings have obliged all parties, intervenors, manufacturers, the AEC, safety engineers, to examine in excruciating detail the possible course of events following a loss-of-coolant accident. The criteria that have emerged represent additional conservatism in the design both of light-water reactors and of their emergency core cooling systems.

I think it is accurate to say that as reactor engineers recognize previously unrecognized potential (and I stress potential) hazards in

nuclear reactors, they are quick to respond with fixes. For example, in a boiling-water reactor, if the electrical load is lost (which occurs on the average of once a year in a big power station) the reactor must be immediately shut down by insertion of "scram" rods. The Advisory Committee on Reactor Safeguards has in recent years asked, Suppose the scram rods all fail to insert under this circumstance - what then? One can argue that failure of all the scram rods to operate correctly is absolutely incredible; yet this did happen in a one-of-a-kind reactor at Hanford a few years ago. The upshot of the matter has been that large boiling-water reactors now incorporate other schemes for shutting off the reactor after a sudden loss of electrical load. This is but one example of how fixes for specific weaknesses are being applied as the possible weakness is spotted.

It is wise to recall periodically throughout this discussion that the events of which I speak are immensely improbable. How improbable, for example, is the failure of the scram rod system? No one can really say - we can't give statistics as we can with traffic deaths where there are millions of separate instances, and our probabilities of fatalities are essentially empirical estimates. To be sure, we can estimate separate branches of a fault tree and arrive at overall probabilities; - these come to one chance in a trillion of a reactor accident that might release one million curies per reactor-year. But such estimates are suspect since they do not deal with common-mode failures - the unexpected fault that nullifies an entire safety system, like the same kind of grit getting into every one of the bearings of a rod drive system. To protect against such common-mode failures one can only follow completely different routes

to safety that are known not to be vulnerable to the same common-mode failure.

To summarize, I cannot say that a serious reactor accident is impossible and will never happen. However, I can say that the probability of this ever happening is extremely small; and further, no matter how small the probability, the reactor community is exerting itself to ferret out and to correct possible weaknesses that could lead to trouble.

Chemical Processing and Transport: I lump these together because if reactors and chemical plants needed for reprocessing their fuel were built very close to each other (in nuclear parks) the transport problem as a separate safety hazard would largely disappear. I therefore have espoused such parks, for example, in my testimony before the Senate Interior and Insular Affairs Committee in October 1971, though I realize there are contrary arguments militating against them - vulnerability to enemy attack, and the local concentration of waste heat, to mention a few. As for the chemical fuel reprocessing plants themselves, we at Oak Ridge National Laboratory are studying measures that might be taken to reduce radioactive emissions from such plants as low as those from light-water reactors - around 5% of radiation levels from natural sources at the plant boundaries. We believe that plants with practically zero release are actually quite feasible and would probably add around .5 mill per kwh to the cost of nuclear power.

But our present technology and philosophy of siting separates the chemical plants from the reactors, and so we are confronted with the

necessity of transporting heavily radioactive materials. To estimate the hazard, let us suppose that by the year 2000, we have 1,000,000 kilowatts of nuclear power, of which two-thirds are liquid-metal fast breeders. There will then be 7000 to 12,000 annual shipments of spent fuel from reactors to chemical plants, with an average of 60 to 100 loaded casks in transit at all times. Projected shipments might contain 1.5 tons of core fuel which has decayed for as little as 30 days (in which case each shipment while in transit would generate 300 kilowatts of heat) and 75 million curies of radioactivity. Present casks from light-water reactors might contain material that produces 30 kilowatts of heat and contains seven million curies of radioactivity.

Design of a completely reliable shipping cask for such a radioactive load is a formidable job. At Oak Ridge our engineers have a design that looks very promising. As now conceived, the heat would be dissipated by transferring it to the surrounding air by use of liquid metal or molten salt; and the cask would be provided with rugged shields which would resist deformation that might be caused by a train wreck. The shipping casks will be designed to withstand a 30-minute fire and a drop from 30 feet onto an unyielding surface.

Can we estimate the hazard associated with transport of these materials? In rail transport in the United States a derailment occurs once per million car miles. Thus, if there were 12,000 shipments per year, each of a distance of 1000 miles, we would expect 12 derailments annually. However, the number of serious accidents would be perhaps 1,000,000- to 10,000-fold less frequent, and the shipping casks are designed to withstand all but the most serious accident (the train wreck

near an oil refinery that goes into flames as a result of the crash). Thus the statistics - a serious accident every 1000 to 100,000 years - at least until the year 2000, look quite good. Nevertheless the shipping problem is a difficult one and may force a change in basic strategy. For example, we may decide to cool fuel from LMFBRs in place for 360 days before shipping: this would reduce the heat load sixfold, and increase the cost of power by only around 0.2 mill per electric kilowatt-hour. The solution that I personally prefer is to cluster the fast breeders in nuclear power parks which have their own on-site reprocessing facilities, and thus eliminate the transport question.

Waste Disposal: The wastes from nuclear reactors will remain radioactive for extremely long times: Plutonium-239 has a half-life of 24,400 years, and wastes containing this nuclide will remain potentially dangerous for 200,000 years. When one speaks of the long-term reliability of nuclear systems, then in the broadest sense one must be prepared to address the question of coping with such wastes responsibly for items longer than mankind has ever had to conceive of his works affecting. Thus, two fundamentally different philosophies have developed with respect to dealing with these wastes. The most obvious is to store them, as rock-like solids, in concrete vaults above ground. This is one of the systems the AEC has under serious consideration, at least for the present. Now vault storage is perfectly feasible and extremely safe - certainly at least as safe as the reactors themselves. However, if one thinks about it for a moment, the prolonged storage in vaults of wastes containing Plutonium-239 requires a long-term commitment by highly intelligent managers of such waste systems. Thus, the price exacted by permanent disposal

of wastes in concrete vaults may be a commitment to a priesthood that will tend the vaults for times unimaginably longer than the time scale of any previous human endeavor.

It is for this reason that the Atomic Energy Commission views concrete vault storage as temporary - say, for 50 to 100 years - and has actively pursued the second approach, that of disposal in underground geologic formations. The great advantage of underground disposal in naturally occurring geologic formations is that in principle the wastes could be sequestered there forever out of contact with the biosphere; and, moreover, no human monitoring would be required once the wastes were in place.

Bedded salt comes very close to being the ideal geological formation, as the National Academy of Sciences recommended in 1955. For example, the Kansas salt deposits have been undisturbed for 200,000,000 years; their continued presence means that they have not been in contact with circulating ground water - for otherwise the beds would have been dissolved.

And indeed, the salt beds are in every respect except one without fault. The only clear weakness of salt for radioactive waste disposal is that one must guarantee that man does not intervene by digging holes (for oil, for example). Holes in the salt might allow water to enter the mine, and the integrity of the salt deposit could then not be guaranteed. Thus, even disposal into geologic formation such as salt may require some human surveillance, almost in perpetuity. The great advantage of such schemes, however, is that the degree of surveillance - amounting merely to preventing people from digging holes - is much less than is required for disposal in aboveground vaults.

Conclusions

We nuclear people have made a Faustian bargain with society. On the one hand, we offer - in the breeder reactor - an almost inexhaustible source of energy. Even in the short range, when we use ordinary reactors, we offer energy that is cheaper than energy from fossil fuel. Moreover, this source of energy, when properly handled, is almost nonpolluting. Whereas fossil fuel burners must emit oxides of carbon and nitrogen, and probably will always emit some sulfur dioxide, there is no intrinsic reason why nuclear systems must emit any pollutant - except heat and traces of radioactivity.

But the price that we demand of society for this magical energy source is both a vigilance and a longevity of our social institutions to which we are quite unaccustomed. In a way, all of this was anticipated during the old debates over nuclear weapons. As matters have turned out, nuclear weapons have stabilized at least the relations between the superpowers. The prospects of an all-out third world war seem to recede. In exchange for this atomic peace we have had to manage and control nuclear weapons. In a sense, we have established a military priesthood which guards against inadvertent use of nuclear weapons, which maintains what seems to be a precarious balance between readiness to go to war and vigilance against human errors that would precipitate war. Moreover, this is not something that will go away, at least not soon. The discovery of the bomb has imposed an additional demand on our social institutions. It has called forth this military priesthood upon which in a way we all depend for our survival.

It seems to be (and in this I repeat some views expressed very well by former Atomic Energy Commissioner Wilfrid E. Johnson) that peaceful nuclear

energy probably will made demands of the same sort on our society, and possibly of even longer duration. To be sure, we shall steadily improve the technology of nuclear energy; but, short of developing a truly successful thermonuclear reactor, we shall never be totally free of concern over reactor safety, transport of radioactive materials, and waste disposal. And even if thermonuclear energy proves to be successful, we shall still have to handle considerable radioactivity.

We make two demands. The first, which I think is the easier to manage, is that we exercise in nuclear technology the very best techniques, and that we use people of high expertise and purpose. Quality assurance is the phrase that permeates much of the nuclear community these days. It connotes using the highest standards of engineering design and execution; of maintaining proper discipline in the operation of nuclear plants in the face of the natural tendency to relax as a plant becomes older and more familiar; and perhaps of managing and operating our nuclear power plants with people of higher qualification than were necessary for managing and operating nonnuclear power plants: in short, of creating a continuing tradition of meticulous attention to detail.

The second demand is less clear, and I hope it may prove to be unnecessary. This is the demand for longevity in human institutions. We have relatively little problem dealing with radioactive wastes if we can assume always that there will be intelligent people around to cope with eventualities we have not considered. If the nuclear parks that I mention are permanent features of our civilization, then we presumably have the social apparatus, and possibly the sites, for dealing with our wastes indefinitely. But even our salt mines may require some small measure of surveillance if only to prevent men in the future from drilling holes into the burial grounds.

Eugene Wigner has drawn an analogy between this commitment to a permanent social order that may be implied in nuclear energy and our commitment to a stable, year-in and year-out social order when man moved from hunting and gathering to agriculture. Before agriculture, social institutions hardly required the long-lived stability that we now take so much for granted. And the commitment imposed by agriculture in a sense was forever: the land had to be tilled and irrigated every year; the expertise required to accomplish this task could not be allowed to perish or man would perish; his numbers could not be sustained by hunting and gathering. In the same sense, though on a much more highly sophisticated plane, the knowledge and care that goes into the proper building and operation of nuclear power plants and their subsystems is something that we are committed to forever, so long as we find no other practical energy source of infinite extent.

Let me close on a somewhat different note. The issues I have discussed here - reactor safety, waste disposal, transport of radioactive materials - are complex matters about which little can be said with absolute certainty. When we estimate that the probability of a serious reactor incident is one chance in 100,000,000 per reactor per year, or that the failure of all safety rods simultaneously is incredible, we are speaking of matters that simply do not admit of the same order of scientific certainty as when we say it is incredible to build a perpetual motion machine. However, we do claim to be responsible technologists, and as responsible technologists we give as our judgment and our promise that these probabilities are extremely - almost vanishingly - small; even though we can never represent these things as certainties. Society must then make the choice, and this is a choice that we nuclear people cannot dictate. We can only

participate in making it. Is mankind prepared to exert the eternal vigilance needed to ensure proper and safe operation of its nuclear energy system? This admittedly is a significant commitment that we ask of society. What we offer in return, an all but infinite source of relatively cheap and clean energy, seems to me to be well worth the price.

July 9, 1973