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The Case for Nuclear Power

Founders Award Lecture
November 18, 1976

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NATIONAL ACADEMY OF ENGINEERING
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NATIONAL ACADEMY OF ENGINEERING

The National Academy of Engineering was established in December 1964 as an organization of distinguished engineers, parallel to the National Academy of Sciences, autonomous in its administration and in the selection of members, and sharing with the National Academy of Sciences under its Congressional Act of Incorporation the responsibility to examine questions of science and technology at the request of the federal government.

The National Academy of Engineering, aware of its responsibilities to the government, the engineering community, and the nation as a whole, is pledged:

1. To provide means of assessing the constantly changing needs of the nation and the technical resources that can and should be applied to them; to sponsor programs aimed at meeting these needs; and to encourage such engineering research as may be advisable in the national interest.

2. To explore means for promoting cooperation in engineering in the United States and abroad, with a view to securing concentration on problems significant to society and encouraging research and development aimed at meeting them.

3. To advise the Congress and the executive branch of the government, whenever called upon by any department or agency thereof, on matters of national import pertinent to engineering.

4. To cooperate with the National Academy of Sciences on matters involving both science and engineering.

5. To serve the nation in other respects in connection with significant problems in engineering and technology.

6. To recognize in an appropriate manner outstanding contributions to the nation by leading engineers.

INTRODUCTION

The National Academy of Engineering established its Founders Award in 1965 to honor outstanding engineering accomplishments by an engineer over a long period of time and of benefit to the people of the United States. The Eleventh Founders Award was presented to Manson Benedict, Institute Professor Emeritus at the Massachusetts Institute of Technology, on the occasion of a banquet for Academy members on April 28, 1976, during the NAE's Twelfth Annual Meeting. Dr. Benedict gave the address traditionally associated with the Award during the Academy's 1976 Autumn Meeting, on November 18. The NAE is pleased to respond with this print to the many requests for copies of Dr. Benedict's address, considered by many to be a most timely and important message.

C.D. Perkins

COURTLAND D. PERKINS
President

RECIPIENTS OF THE FOUNDERS AWARD OF THE NATIONAL ACADEMY OF ENGINEERING

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James S. McDonnell	1967
Vladimir K. Zworykin	1968
Harry Nyquist	1969
Charles S. Draper	1970
Clarence L. Johnson	1971
Edwin H. Land	1972
Warren K. Lewis	1973
J. Erik Jonnson	1974
James B. Fisk	1975
Manson Benedict	1976

MANSON BENEDICT

Dr. Benedict, a member of both the NAE and the National Academy of Sciences and a 1976 National Medal of Science recipient, is known for his outstanding work in the chemical and nuclear engineering fields and especially for his contributions to the gaseous diffusion process for separation of uranium isotopes. His first major professional work was with the M. W. Kellogg Company, where he developed an equation-of-state for gas mixtures and processes for separating hydrocarbons by extractive and aseopropic distillation. During World War II, he was in charge of process design of the K-25 gaseous diffusion plant for separating Uranium$_{235}$ from natural uranium at Oak Ridge, Tennessee.

In 1951, Dr. Benedict joined MIT—from which he received the PhD in 1935—as its first Professor of Nuclear Engineering in the Chemical Engineering Department and was responsible for organizing a program of research and instruction in the new field. Seven years later he became head of a new Department of Nuclear Engineering, a position he held until 1971. He became Institute Professor Emeritus in 1973 and now teaches half-time at MIT.

Dr. Benedict contributed to the work of the U.S. Atomic Energy Commission through membership on its Advisory Committee on Reactor Safeguards and its General Advisory Committee, of which he was Chairman in 1962-64. He was in charge of operations analysis in 1951-52 and assisted in planning expansion of AEC facilities for producing Uranium$_{235}$ and plutonium.

THE CASE FOR NUCLEAR POWER

The 1973 oil embargo showed that the days of low-cost energy were over and that the United States was vulnerable to interruption of energy supplies from overseas. In the three years since then there have been many proposals for greater utilization of our domestic energy resources, but discouragingly slow progress toward adopting them. President Ford's generally sensible energy message of last February failed to gain the support of a Democratic Congress. Now that the elections are over with the President-Elect and Congress from the same party, it is not too much to hope that we shall have a national energy policy which will provide for our future energy needs reliably, at an acceptable cost, with low environmental impact and with minimal risk of interruption from overseas.

I propose to show how increased reliance on nuclear energy can contribute to these goals. Nuclear power plants using light water reactors now have a capacity of 42,000 megawatts and generate about nine percent of the electricity used in the United States. In some parts of the country 40 percent of the electricity now comes from nuclear plants. By the late 1980s reactors now in operation, under construction and on order will have a capacity of over 208,000 megawatts, about 30 percent of the total U.S. capacity expected at that time. If the further projected expansion of nuclear capacity takes place, over 400,000 megawatts of nuclear power should be in operation by the end of the century, generating around 50 percent of U.S. electricity.

The incentives for this increased adoption of nuclear power are its lower cost, the security of its fuel supply and its lower impact on human health and the environment compared with oil and coal.

Nuclear-generated electricity has an advantage over coal and oil both in costs from plants operating today and in costs projected for plants now under construction. In 1975 the average cost of electricity generated in nuclear plants was 1.23 cents per kilowatt-hour, compared with 1.75 cents/kwh from coal and over two cents from oil. Nuclear plants generated 170 billion kilowatt hours whose total cost was a billion dollars less than if generated from coal at coal's average cost, or two billion dollars less than from oil at oil's average cost.

Nuclear electricity has the greatest cost advantage over coal in large, base-loaded stations at sites remote from low-cost, strip-mined low-sulfur coal. In Montana and Wyoming, for example, with their large deposits of such coal, nuclear generated electricity is not economical compared with coal. On the other hand, in California, Chicago and the Atlantic states, economic studies invariably show a substantial cost advantage for nuclear power because of the high cost of bringing in low-sulfur coal from mines a thousand miles away or the high cost of sulfur-removal systems for plants burning high-sulfur local coal. For example, studies by the Commonwealth Edison Company predict that in Chicago in the mid 1980s, electricity from the base-load nuclear stations that company is building will cost 18 percent less than from coal-fired plants, or 32 percent less than from oil. A 1975 study by Arthur D. Little, Inc. and S. M. Stoller Corporation for New England Electric Company predicts that for base-load plants coming into service in the mid 1980s in New England, the average cost of electricity over the next 20 years from a nuclear plant would be 26 percent less than from coal. Testimony by the General Electric Company before the Connecticut Public Utility Commission in January 1976 predicted a 30 percent lower cost for nuclear generated electricity than from coal.

Critics claim that nuclear plants are unreliable, but statistics fail to confirm this. During 1975 U.S. nuclear plants were available 74 percent of the time and generated 64 percent of their rated capacity. Oil plants had a 70 percent availability and 42 percent capacity factor, and coal plants an 80 percent availability and a 55 percent capacity factor. Although the nuclear plants' availability was less than hoped for, it was comparable with coal and oil. Moreover, 13 percent of the nuclear plants' down time was for scheduled maintenance and refueling. Thus, nuclear plants are proving as reliable as other large electric generating stations. In addition, nuclear plants have the big advantage over fossil-fueled plants of security of fuel supply. Once charged with fuel a nuclear plant will operate for a year without refueling, whereas a coal or oil-fired plant is vulnerable to interruption of fuel supply by strikes in mines or transport, or embargo, in the case of oil.

Despite all the concern about the occupational and public health hazards of nuclear plants, studies comparing fatalities or injuries from nuclear power systems with those from coal invariably conclude that nuclear plants are far less harmful. For example, a 1973 report of the Council on Environmental Quality reported that, from the generation of 200 billion kilowatt hours of electricity, there were 4.6 occupational deaths in nuclear systems (practically all in uranium mining) compared with 79 in systems using surface-mined coal and 120 with deep-mined coal. Statistics on frequency of injuries and lost time from accidents are in roughly the same ratios favorable to nuclear.

Turning next to public safety, it cannot be emphasized strongly enough that no member of the U.S. public has ever been injured, much less killed, as a result of accidents in nuclear power plants. This remarkable safety record for a potentially hazardous new technology is a striking example of what can be done to protect the public when risks are identified and proper precautions taken in design, operation and regulation. Nevertheless, it is recognized that there is a finite probability of accidents in nuclear plants in which people might be harmed. The study for the Nuclear Regulatory Commission directed by Norman Rasmussen of the Massachusetts Institute of Technology concluded that the total effect of the entire spectrum of possible accidents might lead to an average of 0.8 accidental deaths and eight injuries per year for the production of 200 billion kwh of nuclear electricity. A study and critique by the American Physical Society would increase these by a factor of around three mostly because of exposure of people for down-wind and time-persistent effects. Even so, the effects are small compared with recent studies on the health effects of generating electricity from coal, which estimate at least 600 deaths per year for the same electric output. A corresponding figure for nuclear plants, obtained by David Rose in a recent study and taking all industrial and civilian consequences of nuclear generation into account, is 11 deaths per year.

At one time concern was expressed about the long-term health and genetic effect of low-level radiation from normal operation of nuclear power facilities. This concern has been largely dispelled by the strict control of effluents practiced at these facilities in conformity with government regulations that exposure of the public to radiation be kept as low as practicable. The result has been that exposure of the public to radiation from nuclear plants has been far less than one percent of the natural background radiation we are all exposed to.

At present great concern is expressed about possible catastrophic consequences of sabotage of nuclear facilities by irrational or malevolent groups. Nuclear plants are much more readily protected against disabling sabotage than fossil-fueled plants. Nuclear plants have no vulnerable external coal pile or tank farm and store a year's fuel supply in the reactor itself, protected by its own radioactivity and radiation shield. The massive reactor shield and shielded primary piping provide substantial physical protection against destruction by saboteurs. The emergency cooling systems provide redundant protection against offsite effects even if the primary cooling systems were damaged. The need for prevention of intrusion by saboteurs is clearly recognized by the Nuclear Regulatory Commission. Every nuclear facility is required to have an elaborate, and necessarily unpublicized, system of physical security including barriers, alarm systems, armed guards and coordination with local authorities, which should effectively prevent intrusion.

The public is greatly concerned about the disposal of nuclear wastes. These, too, can be dealt with safely, but federal authorities have admittedly been slow to implement a proper long-term solution. I have been a member of the National Research Council's Committee on Radioactive Waste Management.* Our Committee is convinced that technical measures are available for the safe packaging, transportation and long-term storage of these wastes with miniscule risk to the public. The Energy Research and Development Administration (ERDA) now recognizes the importance of demonstrating that reliable technology is available and hopefully will be able to convince the American public and receive approval to activate a nuclear waste repository. The preferred procedure is as follows. Spent fuel from nuclear power plants should be shipped to a reprocessing plant where uranium and plutonium would be separated and freed of contaminating radioactivity and radioactive wastes would be converted to a water-insoluble glass. The volume of wastes is not large; one 1000 megawatt power plant produces only 80 cubic feet of waste per year. This waste would be packaged in seal-welded stainless-steel containers and shipped in shielded carriers to a federal waste repository. This repository would be a geologic formation 500 meters or more below ground known not to be subject to permeation by flowing water. The type of geologic formation preferred by our Committee is bedded salt, whose very existence is evidence of absence of flowing water. Other advantages of salt are its relatively high thermal conductivity and its plasticity, which assures healing of fissures after possible earth movement. Other possible formations are igneous or sedimentary rocks in arid regions. The first attempt by the Atomic Energy Commission to establish a pilot waste repository in an abandoned salt mine in Kansas failed because of local opposition and failure to note that the integrity of the salt bed had been spoiled by solution mining of salt near the proposed repository. There are numerous other salt deposits in the United States demonstrably free from nearby water intrusion. The principal problem in using one of them is gaining understanding and acceptance from the local public that the waste repository need not be harmful, that the wastes deep underground will remain in place till no longer hazardous and that the repository will have positive economic benefits for the region.

Another aspect of nuclear power which causes great concern today is possible diversion of fissile material for fabrication into a bomb by terrorists. The fuel for today's reactors, uranium enriched to around three

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*The Committee is a unit within the Commission on Natural Resources of the National Research Council, the "operating arm" of the National Academy of Sciences and the National Academy of Engineering.

percent in $\mathrm{Uranium}_{235}$, is too dilute for use as an explosive. On the other hand, plutonium, which will be separated in reprocessing plants for use either as an optional fuel in water-cooled reactors or as an essential fuel in breeders, could be made into a crude bomb by a terrorist given time and the requisite skills. To appreciate how diversion can be prevented, let us follow plutonium through the nuclear fuel cycle. In spent fuel leaving the reactor, plutonium is diluted with millions of curies of radioactivity which thoroughly prevents theft during spent fuel storage and shipment to a reprocessing plant. At this plant, after separation from fission products, decontaminated plutonium oxide would be in the form most immediately useful in an illicit explosive. Here it must be carefully guarded. Although present ideas are to permit shipment of pure plutonium oxide to a fuel reprocessing plant at a separate site, I believe that this involves the unnecessary risk of theft during transportation. I would recommend that the plutonium oxide never be shipped in pure form, but be mixed with uranium oxide in the right proportions for reactor fuel and fabricated into fuel assemblies at the reprocessing plant. These assemblies weighing a half ton or more would be much less vulnerable to theft during subsequent shipment to a nuclear power plant than pure plutonium oxide and would require time-consuming disassembly and chemical separation before fabrication into a bomb. If further precaution against theft were deemed necessary, the finished assembly could be made radioactive by brief irradiation at the fabrication plant. In such a system, the only place where pure plutonium unprotected by intense radioactivity would be handled would be at the plant where both reprocessing and fabrication are carried out.

Adequate physical security and armed guards at this one facility would ensure against diversion. Since one facility could serve 60,000 megawatts or more of nuclear power plants, the number of armed guards needed would not be large and would not create a police-state climate, as some have claimed. This expedient would make unnecessary the segregation of nuclear power plants fueled with plutonium in so-called nuclear parks equipped with reprocessing and fabrication facilities, which are being recommended by some authorities as a solution to the plutonium diversion problem.

Another concern often expressed about nuclear power is that it facilitates the spread of nuclear weapons to countries which do not now have them. This is unfortunately true if such countries build fuel reprocessing plants, but it is not a valid argument against the expanded use of nuclear energy within the United States. Moreover, placement of reprocessing plants under international control would effectively prevent diversion of civilian plutonium to military uses.

A final objection sometimes raised against nuclear power is that the amount of uranium in the United States is insufficient to make its development worth while. Present ERDA estimates are that there are 640,000 short tons of uranium oxide in reasonably assured reserves, and that a total of around 3,600,000 short tons of economically useful uranium oxide may be extracted from these deposits and others to be discovered in further exploration. Present water-cooled reactors consume about 150 tons of uranium oxide per year per thousand megawatt plant; 640,000 tons is enough to fuel the 208,000 megawatts of nuclear capacity now on order for over 20 years, and 3.6 million tons, if found, would fuel 400,000 megawatts for 60 years. Thus, we have enough uranium to make today's light water reactors a valuable addition to our electric power industry, but not enough to provide for electric needs far into the future.

The energy potential of nuclear fuel resources can be greatly extended by development and industrial deployment of the breeder reactor. This reactor uses not only the scarce isotope Uranium_{235} which makes up only 0.7 percent of natural uranium, but also the abundant isotope Uranium_{238}, by converting it to plutonium. A breeder reactor consumes only about two tons of uranium oxide per year per thousand megawatt plant, about one seventieth the consumption of a water-cooled reactor. The 3.6 million tons of uranium oxide would fuel a 400,000 megawatt breeder power system for 4500 years. It is this enormous extension of our energy resources which makes the breeder such an important element in our energy future. Another view of the importance of the breeder may be gained by noting that the amount of electricity which could be generated from the 150,000 tons of depleted uranium now in storage at ERDA's uranium enrichment plants, if used as fuel in breeders, could generate as much electricity as 400 billion tons of coal, which is close to all the commercially minable coal in the United States. And this depleted uranium has already been mined, costs practically nothing and can be used without risking a single miner's life. Moreover, the breeder will make efficient use of the stock of plutonium produced as a by-product of water-cooled reactors.

Although ERDA's National Plan for Energy Research, Development and Demonstration lists the breeder reactor together with solar energy and fusion as one of the "essentially inexhaustible" energy sources still to be developed, the breeder is much closer to practical economic use for electric power generation than solar energy or fusion. Solar energy, though very valuable for low-temperature comfort and process heating, is too diffuse, too variable with time of day or season and too uncertain because of weather to be competitive economically with the breeder for major electric power generation. Fusion is a brilliant scientific concept well worth the major development effort it is receiving, but with many major unsolved engineering problems which leave it far from certain ever to generate a single kilowatt of economic electric power.

The liquid metal fast breeder on the other hand, has already repeatedly demonstrated its ability to generate electricity. The very first reactor in the world to generate electricity was Experimental Breeder Reactor number one, which ran a small generator in Idaho in 1951. Experimental Breeder Reactor number two has been generating 20 megawatts of electricity in Idaho for the past ten years. In France, the 250 megawatt Phenix fast reactor has been operating since 1974 with an availability higher than light water reactors. The success of Phenix has led to plans in France to rely heavily on full-scale versions of Phenix for commercial electric generation in the 1980s. The United States has started design and construction of the 350 megawatt Clinch River Breeder Reactor, scheduled for operation in Oak Ridge in 1983.

These breeder reactors all use liquid sodium as reactor coolant. Because the sodium becomes very radioactive, it is considered desirable to transfer heat from the radioactive sodium to a secondary inert sodium circuit before transferring heat from sodium to water to make steam. It is recognized that the initial cost of this type of breeder reactor will be higher than a water-cooled reactor of the same capacity, because of the extra sodium system and the higher cost of handling sodium compared with water. However, the fuel cost of the breeder reactor will be much less than that of the water-cooled reactor because the breeder is spared the costs of natural uranium and uranium enrichment. Studies by ERDA and by Dr. Thomas Stauffer of Harvard, General Electric and Commonwealth Edison show that the initial cost of the breeder could be at least 25 percent more than the light water reactor and still permit the savings in fuel costs to provide a favorable financial return on the higher investment in the breeder and the estimated ten billion dollars needed to complete its development and commercialization. I see no reason why a commercial breeder need cost more than 25 percent more than a light water reactor power plant of the same capacity.

The principal objections to the breeder have been the toxicity of its plutonium fuel, risk of theft of plutonium by would-be terrorists, and the possibility of a small nuclear excursion from maloperation of the reactor. Let me dispose of these objections one at a time. Techniques for safe handling of plutonium and the far greater number of curies of accompanying fission products have already been worked out by ERDA in its fuel reprocessing and fabrication plants, where there have been no instances of serious plutonium poisoning in over 20 years of handling large amounts of this toxic material. Theft of plutonium can be prevented by the same measures which were discussed for light water reactors.

The Clinch River breeder will have two independent and redundant reactor shutdown safety systems. Despite this, it has been postulated that both might fail to operate at the same time that the sodium circulation stopped so that the sodium would boil away and the fuel would melt and reassemble quickly enough in a super-critical configuration to produce substantial energy release.

Estimates of the mechanical effects of such an improbable combination of events are very uncertain, but effects equivalent to 1200 megajoules of mechanical energy have been postulated. Three measures for preventing or mitigating the effects of such an unlikely accident are 1) confinement of the reactor core by a structure strong enough to remain intact after the postulated event; 2) provision of an internal blanket of nonfissile Uranium$_{238}$ to reduce the energy release from a super-critical event; and 3) construction within the reactor of a self-contained shutdown device, a "reactor fuse," which would respond directly to an increase in power and insert a control absorber without intervention of an external control system. The first measure is being required by the Nuclear Regulatory Commission for the Clinch River Plant, and the second is being considered. I believe that the third also has merit. Each of these measures should effectively eliminate offsite effects from a nuclear excursion in a fast reactor.

I would like to conclude this assessment of the problems and potential of nuclear energy by making the following recommendations for U.S. energy policy:

1) We should accelerate the substitution of electricity, largely nuclear generated, for oil and gas, recognizing our limited resources of these hydrocarbons and their unique value as chemical feed stocks and automotive fuels.
2) Uses where electricity could advantageously be substituted for oil and gas include space heating by the heat pump, electrification of the railroads, and short-haul highway transportation by electric auto and truck.
3) We should facilitate the construction and operation of additional water-cooled nuclear power plants by providing better public understanding of their advantages and benefits and reducing the delays in their construction caused by protracted and obstructively contested licensing proceedings.
4) Because uranium resources are limited and commercial development of a new energy system takes many years, we should expedite development of the breeder. The Clinch River Plant should be completed as soon as possible, and larger plants should be built as soon as technical reliability can be assured. Breeders are our

> best hope for generating electricity at lower cost than any alternative energy source in the last decade of this century. What is needed now is the will and determination to develop this unique energy source, which is the only assured way we now have to supply our electric energy needs for thousands of years.

The United States is fortunate that nuclear energy has become available just when other energy sources are beginning to fail. We should use it fully, and wisely.