Medical perspective on nuclear power

Summary of a report by the American Medical Association's Council on Scientific Affairs

Is generating electricity with nuclear power safe in the United States? Could the explosion of a nuclear power reactor cause widespread dissemination of radioactivity, as the Chernobyl explosion did in 1986? How do power reactors operate, and what principles safeguard their operation? What should be the role of the physician with regard to nuclear power? A recent report of the Council on Scientific Affairs of the American Medical Association (AMA) considered such questions. The report, prepared by an expert committee, received the endorsement of the AMA's House of Delegates. Major issues delineated in the report and all of its conclusions appear in this summary.

Catawba nuclear plant, USA.

Since the mid-1800s in the United States, energy use has grown steadily as energy availability has increased and energy cost has decreased.[1] In the United States, the increasing use of energy has led to industrialization, faster transportation, increased productivity, improved quality of life, and better health. At present, the generation of electricity accounts for approximately one-third of the nation's energy use. In 1960, 0.1% of US electricity was generated by three operating reactors; in 1987, approximately 18% of electricity was generated by 106 operating reactors.[2]

Yet during the 1980s, nuclear power became less attractive to some. The partial core meltdown at Three Mile Island in 1979 (and the steam-hydrogen explosion at Chernobyl in 1986) increased concerns about safety, and construction and operating costs escalated. Long delays in licensing and operation occurred, many because of federal regulations. Orders for nuclear power plants were cancelled and the construction of other plants was halted. While no new application for a nuclear power plant has been filed since 1977, on the other hand, referenda in several States to prohibit nuclear power have failed.

Nuclear power plants

Nuclear power reactors use energy released by nuclear fission to generate electricity. In fission, heavy atomic nuclei such as those of uranium-235 split to form lighter nuclei, releasing an enormous amount of energy. The core of a reactor contains thousands of long, narrow, thin-walled, zirconium alloy tubes packed with nuclear fuel pellets, each approximately 2 1/2 cm long and 1 1/3 cm in diameter. Fission is induced in the fuel by the capture of low-energy neutrons. During fission, each atom releases two or three "fast" neutrons, which, if slowed, can contribute to a self-sustaining chain reaction. Neutron slowing is accomplished with a "moderator," that is, a substance of low atomic number such as water or graphite.

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Most US power reactors are called "light-water reactors" (LWRs) because they use water to moderate the speed of neutrons and cool the nuclear fuel. There are two types of LWRs, the pressurized-water reactor (PWR) and the boiling-water reactor (BWR). In both types, the reactor is contained in an airtight steel pressure vessel, which has walls 15 to 25 cm thick, is 360 to 450 cm in diameter, and 12 m or more high, and is designed to contain unintended releases of radioactivity.

In a typical pressurized-water reactor, water heated in the reactor core is circulated to a steam generator, where some of the heat is transferred to water at a lower temperature and pressure, causing it to boil and create steam that operates the electricity-producing turbine *(See accompanying figures)*. Low-pressure steam exhausted from the turbine is condensed and returned to the steam generator by the feedwater pump. Water that circulates through the condenser cooling loop to a cooling tower or nearby body of water is not radioactive. In a BWR, steam generated in the reactor core passes through a moisture separator in the top of the vessel and directly to the steam turbine.

The products of nuclear fission are radioactive, and the reactor fuel becomes radioactive and thermally hot as the reactor is operated. Most of this radioactivity, amounting to approximately 111×10^{19} bequerel (Bq) in a typical reactor, is trapped in the fuel pellets, which would melt if they were not cooled. One of the major safety issues with LWRs is providing reliable methods of removing this heat of radioactivity under various postulated conditions of systems failure.

An important safety feature of all LWRs built in Western nations is that they are designed to have *negative* void coefficients. This means that as the temperature of the reactor core increases, the changing of water to steam creates additional empty spaces of "voids" in the core, which leads to a reduction in power. The reactor at Chernobyl had a *positive* void coefficient, that is, power *increased* as water changed to steam in the reactor core. This unfavourable characteristic, combined with serious violations in operating procedures and the lack of an effective containment structure, led to the steam-hydrogen explosion and the widespread dispersion of radioactivity at Chernobyl.[3,4] The Chernobyl disaster would not have occurred in a reactor with a negative void coefficient, which is characteristic of all US nuclear power plants. Thus, a Chernobyl-type event cannot occur at a US nuclear power plant.

Nuclear fuel cycle

Generation of nuclear power requires access to facilities for mining and refining uranium, fabricating fuel, using fuel to generate electricity, disposing of spent fuel, and transporting and managing radioactive materials *(See accompanying figures)*.[5] When a reactor core that contains uranium-235 reaches the end of its useful life, approximately half of the uranium-235 has been consumed and a small fraction of the uranium-238 has been transmuted to plutonium-239 and other transuranic elements. Currently, spent fuel is stored at the power plants where it is generated, pending approval for and completion of construction of a high-level waste storage facility.

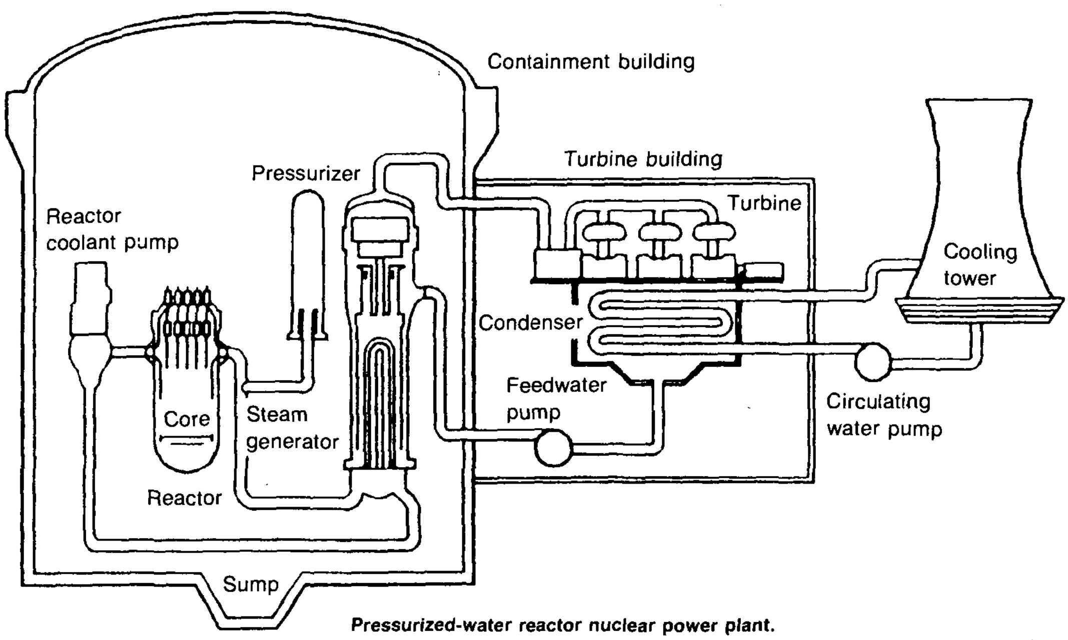
Approximately 2.8 million shipments of radioactive material that contain approximately 33.3×10^{16} Bq, not including shipments of spent fuel, occur each year in the United States.[5] Primary responsibility for regulating the shipments is with the US Department of Transportation, and the regulations depend of the types and amounts of radionuclides and vehicles involved. Most shipments are of relatively innocuous materials that can be transported safely in fiberboard or wood boxes or steel drums ("type A" packages). Intermediate quantities of radioactive materials are shipped in "type B" containers, which must meet more rigorous standards. Shipments of high-level wastes, spent fuel, and transuranic wastes involve large amounts of radioactivity and require more protection. The heavy casks for shipping these wastes are subject to severe tests before they are accepted by the responsible federal agencies.[5]

In the management of radioactive wastes, the technical aspects are less challenging than the sociopolitical ramifications. The major problem is that people in each locality want the wastes shipped somewhere else. Radioactive wastes are classified according to their physical and chemical properties and by origin. By law, wastes that originate from national defense programmes must be handled separately from those produced during civilian uses. The half-life and chemical form of the wastes also influence their management.

Low-level wastes include residues from laboratory research, such as contaminated paper and biological materials, and weak radioactive waste from nuclear power plants, such as cloth, plastics, scrap metal, and building materials. Two other categories have accumulated in large volumes at a few sites — uranium mill tailings and wastes generated during cleanup operations at uranium, radium, and thorium processing plants.

Public exposures to radiation from low-level waste disposal operations have been small compared with those from natural and medical sources. However, some problems with the operations have arisen in the past. In 1980 and 1985, the US Congress passed legislation that will require each state, by 1 January 1983, to dispose of low-level radioactive wastes generated within its borders and encourage States to form "regional compacts" to select common disposal sites. A recent AMA report (Report A, 1988 Interim Meeting) reviews the subject of low-level radioactive wastes.

High-level wastes are of two types — unreprocessed spent reactor fuel and liquid and solid residues from reprocessing the spent fuel. Transuranic wastes, most of which are from weapons production, also are produced. Several methods of isolating high-level wastes have been studied during the past 40 years, including on-site



Pressurized-water reactor nuclear power plant.

solidification, geological isolation, burial in the seabed and subseabed, and injection as a grout into deep rock fissures.[6,7] Geologic isolation in mined cavities, using a multibarrier approach, appears to be the most viable option for disposal. Federal legislation passed in 1988 calls for exploring Yucca Mountain, Nevada, as a possible national repository for high-level wastes.

Some major issues characterize the assessment of risk for disposing of radioactive wastes. First, no historical precedent exists for the long period during which risk assessment will be required. Also, development of criteria for a high-level waste facility has been handicapped by the slow evolution of thought about radiation dose limitations that can ethically be imposed on future generations. A properly designed facility easily could satisfy the dose limits prescribed by the US Nuclear Regulatory Commission (NRC) for LWRs, that is, 0.10 to 0.25 millisievert (mSv) per person per year.

Several investigators have used models in nature to infer the behaviour of radioactive waste in a deep geologic repository.[5] Study of the models, involving the Oklo uranium mine in West Africa and a large deposit of thorium and rare earths in Minas Gerais, Brazil, show that natural mineral deposits may be stable over geologic time.

Normal operations of a nuclear power plant

In mid-1987, the 106 nuclear power reactors operating in the United States included 68 PWRs, 37 BWRs, and 1 high-temperature, gas-cooled reactor. Radiation exposures to power plant workers and the general public tend to be somewhat higher from older power plants and those with BWRs. The primary sources of workers' exposures are from corroded materials from the metal surfaces of valves and pipes and from structures within the core. These materials, made radioactive during reactor operations, are from normally occurring impurities in the alloying elements of steel used to manufacture components. Minute amounts of uranium left on the surface of fuel elements during their manufacture and uranium and fission products that escape during normal operations because of slight imperfections in the fuel rod cladding are of less importance.

Workers are exposed to radiation primarily during major reactor maintenance and refuelling operations, which are performed when the reactor is shut down. The largest radiation doses occur during major maintenance work that includes the following: disassembly and reassembly of valves; removal and replacement of access ports in the primary water systems; testing, decontaminating, cleaning, and plugging steam generator tubes in pressurized-water reactors; inspection and corrective maintenance in BWRs; and removal and replacement of the tops of reactor vessels and internal equipment to permit refuelling. Exposures also occur during plant decontamination operations and radioactive waste disposal. The best estimate of the total impact of the nuclear power industry on health is the collective radioactive dose in the industry. In 1986, the average collective dose to all workers was 4.8 person-sievert (Sv) per PWR plant and 6.5 person-Sv per BWR plant. The average dose was 4 mSv per worker, and doses to the most highly exposed workers were well within NRC-specified limits. Monitoring and surveillance of workers' exposures by power companies, contractors, the US Institute of Nuclear Power Operations (INPO), and the NRC help to ensure that these do not exceed federal exposure standards.

In 1974, the NRC required that operating power reactors be designed or backfitted so that their effluents produce radiation doses to the surrounding population that are "as low as reasonably achievable." The NRC specified an upper limit of 0.05 mSv/year (y) whole-body dose from airborne gaseous releases, 0.15 mSv/y to the thyroid from released radioiodines, and 0.03 mSv/y from liquid effluents to any individual at the site's boundary or beyond. These limits are small fractions of the 3 mSv/y average dose to individuals from natural background radiation.[8]

After the Three Mile Island emergency, both the NRC and the nuclear power industry increased their attention to radiation protection programmes. The focus of much of the industry's activity in this respect was INPO. Today INPO and the utilities that operate nuclear power plants support extensive radiation protection and training programmes to maintain exposures that are as low as reasonably achievable. Almost all power reactors are operated so that radiation doses from effluents are far below the prescribed limits. Doses typically are less than 0.001 mSv/y to the whole body and less than 0.01 mSv/y to the thyroid from all pathways. In 1983, the most recent year for which data have been released by the NRC, the total dose attributable to effluent releases from the 80 power reactors then in operation was 0.95 person-Sv from airborne pathways and 0.76 person-Sv from liquid pathways. The average dose to persons who lived within 80 km of the reactors was 4×10^{-5}mSv.

Unplanned radiation releases

The design of a US nuclear power reactor is such that it cannot explode like a nuclear weapon. Also, the fissile uranium-235 in the reactor is diluted extensively with uranium-238, and the rate at which the power level can increase is limited to values well below those required for a weapons-type energy release. However, a power reactor contains much radioactivity in its core, and releases of a significant fraction of this radioactivity could cause considerable damage to people's health and property and to the environment.

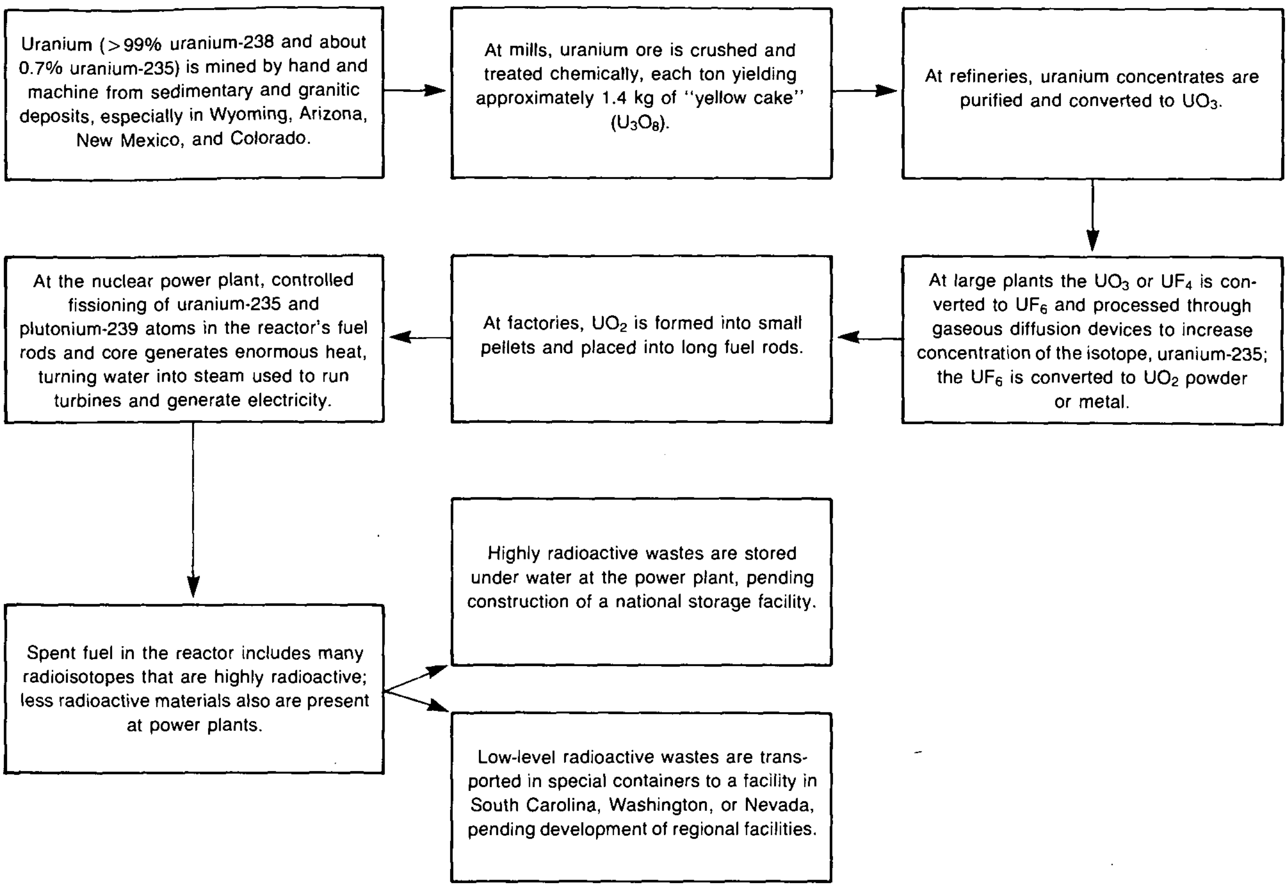
Only those conditions or events that lead to the melting of fuel in a reactor can cause serious public health consequences. In the type of power reactor used in the United States, the situation of greatest concern is one in which the chain reaction is stopped but the systems for removing heat from the reactor core fail to function. In this situation, the temperature will rise rapidly until the fuel's melting point is reached. At Three Mile Island, a valve that was stuck open caused a loss of cooling water, and an operator shut off the emergency cooling water in error. The result was a partial meltdown of the reactor core.

Some radioactive fission products are volatile at the high temperature at which reactor fuel melts, and these volatile products are released from molten fuel as fine particles or aerosols. A sizeable fraction of the aerosols would stick to cooler metal surfaces in the reactor, a process known as "plating out". Also, the fission product removal system, which involves either sprays or large pools of water, would begin to operate. Some fission products in reactors are radioactive isotopes of the noble gases, xenon and krypton. Because of their inert nature, these gases are not of concern in an atmospheric release.

The health consequences of a core meltdown depend on the probability that chemically active fission products will breach the containment vessel. A 1975 report of the NRC analysed the operations of LWRs and concluded that the probability of a core meltdown is approximately 1 in 20 000 per year per reactor.[9] The uncertainty in this estimate is a factor of 10, so the probability actually lies between 1 in 2000 and 1 in 200 000 per reactor. The report also concluded that less than 1% of core meltdowns would release life-threatening amounts of radioactivity. From the NRC estimates, one may conclude that if 100 nuclear power plants operated in the United States for 10 years, then the probability that a core meltdown would lead to the release of life-threatening amounts of radioactivity during the 10 years would be $100 \times 10 \times 1/20\ 000 \times 1/100$, or 1 in 2000. This calculation, however, does not consider the improved safety that has accumulated in nuclear power plant design and operation.

Knowledge about the characteristics of radioactive releases from nuclear power plants is useful in designing programmes to protect the public if there should be a release. Initial exposures from released radioactivity are less if people remain inside closed buildings because buildings provide some shielding from external radiation and reduce exposure to airborne radioactivity. The dose reduction is modest inside frame buildings without basements, and greater still inside large commercial buildings.

If a major release occurred, the preferred strategy for most individuals, except those within a few kilometers of the power plant, would be to take shelter in homes and buildings and wait until the initial release of radioactivity, that is, the "radioactive cloud", moved out of the area. Areas with extensive radioactive contamination should then be evacuated. Even in the worst scenario that can be envisioned, evacuation would be possible several hours after the cloud had passed. Having people wait several hours in their homes accomplishes three purposes. First, it reduces the number of people who must be evacuated immediately; second, it keeps people sheltered while the cloud is in the area; and third, it helps reduce panic. After the cloud has passed, authorities can determine which areas have been contaminated and provide further instructions.



Origin, manufacture, and disposal of nuclear fuel in the United States. (Source: National Geographic (1979)[5])

The Chernobyl explosion released billions of megabecquerels to the environment. Still, evacuation was not initiated for approximately 48 hours. Those who stayed indoors received an average exposure of approximately 0.03 gray (Gy), while the dose to unsheltered persons was 0.1 to 0.15 Gy.[10] The medical response after the explosion specified three levels of care: rescue and first aid at the plant, emergency treatment in regional hospitals, and evaluation and treatment at a specialized center in Moscow.

If exposure to radioactive iodine occurs, a blocking agent such as potassium iodide may be used to prevent uptake of the radioiodine. The blocking agent should be used in a timely fashion and according to recommendations of the US National Council on Radiation Protection and Measurements.[11] After the Chernobyl explosion, Russian medical authorities distributed iodine to all children's institutions in the area; use of the iodine was considered to be highly effective.[12]

A wide range of exposures would be expected from a severe radiation release. At the high end, exposures to more than 2 Sv would cause radiation illness in many people and might be life-threatening to a few. Only with a total breakdown in civil and public health protection would one expect to have more than a handful of people, excluding plant personnel, in this group. The Chernobyl experience seems to bear this out; no member of the general public received a dose capable of producing radiation illness. However, 100 persons received doses greater than 1 Sv, and 31 plant workers and firemen died of burns and radiation injury.[3,10]

A radiation release might expose a large number of people to doses in the 0.1 to 1-Sv range. Although these persons would not be expected to experience radiation-induced illness, they probably would experience stress and apprehension. A greater number of people might receive exposures below 0.1 Sv and require no treatment other than decontamination. In the Chernobyl explosion, this group included at least 100 000 persons.[10] As the Three Mile Island emergency showed, persons who live in a region where a release occurs but have no measureable exposure nevertheless may exhibit anxiety-induced symptoms.

As described earlier, LWRs in the United States are not susceptible to a Chernobyl-type disaster. A core meltdown combined with failure of containment conceivably might release a quantity of radioactivity approaching that released at Chernobyl. Scenario analysis suggests, however, that an outcome similar to the one at Three Mile Island is far more likely. In that case, the reactor's containment worked well, and the release was estimated to be approximately 37×10^{16} Bq of noble radioactive gases and less than 111×10^{10} Bq of radioiodine. No person outside the confines of the power plant received a dose greater than 1 mSv.

Long-term effects of radiation exposure can include cancer, thyroid disease, cataracts, and, possibly, genetic anomalies. The frequency of these effects in an exposed population is usually estimated from the collective dose to the population under the conservative assumption that there is a linear relationship between dose and effect.

The whole-body population dose from a core meltdown is estimated to range from 10 person-Sv if the containment is effective to as much as 10^6 person-Sv if everything fails in the worst possible way. A "rule of thumb" is that 200 to 400 fatal cases of cancer might result from a population exposure of 10 000 person-Sv; however, the possibility of fewer, or even no, deaths cannot be excluded.[13] Hence, a collective dose of 10^6 person-Sv might cause as many as 40 000 fatal cases of cancer during the next several decades. These cases probably would occur in a large population around the power plant, among perhaps as many as 10 million persons. In such a population, approximately 1.9 million fatal cases of cancer would occur "naturally". The radiation would increase this number by less than 2%, and this effect would be difficult to detect.

A more likely consequence of the worst foreseeable radiation release would be the occurrence of additional thyroid nodules at a rate similar to the spontaneous rate. Genetic effects probably would occur at less than 0.1% of the natural rate and would be unobservable.[14]

Risks related to nuclear power

Generating electricity by any means entails some risk; for instance, 166 persons died in a July 1988 explosion on a North Sea oil rig. Underground coal mining is one of the most hazardous occupations, and in the United States approximately 100 persons are killed annually at grade crossings during the transport of coal to power plants. Emissions from the combustion of coal contribute to air pollution and disease, and the ash and residue of coal combustion must be disposed of. All of these activities involve risk.

The US Environmental Protection Agency, the NRC, and other federal regulatory agencies have attempted to regulate the fuel cycles of energy-producing technologies to eliminate unreasonable risk. For example, new performance standards for large coal-fired boilers limit emissions of sulphur oxides and particles; underground mining has been regulated to lower the incidence of injuries and coal worker's pneumoconiosis; and the public's exposure to radiation from the nuclear fuel cycle is regulated. As a result, present coal and nuclear power plants probably are safer than those of two decades ago.

In the early 1970s, Sagan, as well as Lave and Freeberg, compared the public health risks of various energy-generating technologies, and concluded that in comparison with the coal-fired plants, nuclear power offered substantially lower risks to the public's health. Hamilton's study from Brookhaven National Laboratory in Upton, NY, reinvestigated the issue in 1974 and reported that a modern coal-fired plant still is not as safe as a nuclear power plant.[15,16,17]

For coal, underground mining and air pollution dominate both the morbidity and mortality estimates, followed by the hazards of transport. If coal is mined underground and transported by rail, the fuel cycle from mining to combustion is estimated to produce 279 illnesses and injuries, along with 18.1 deaths per gigawatt-year.[17] In contrast, the nuclear fuel cycle, with the uranium mined underground, is estimated to produce 17.3 cases of illness and injury and one death per gigawatt-year.

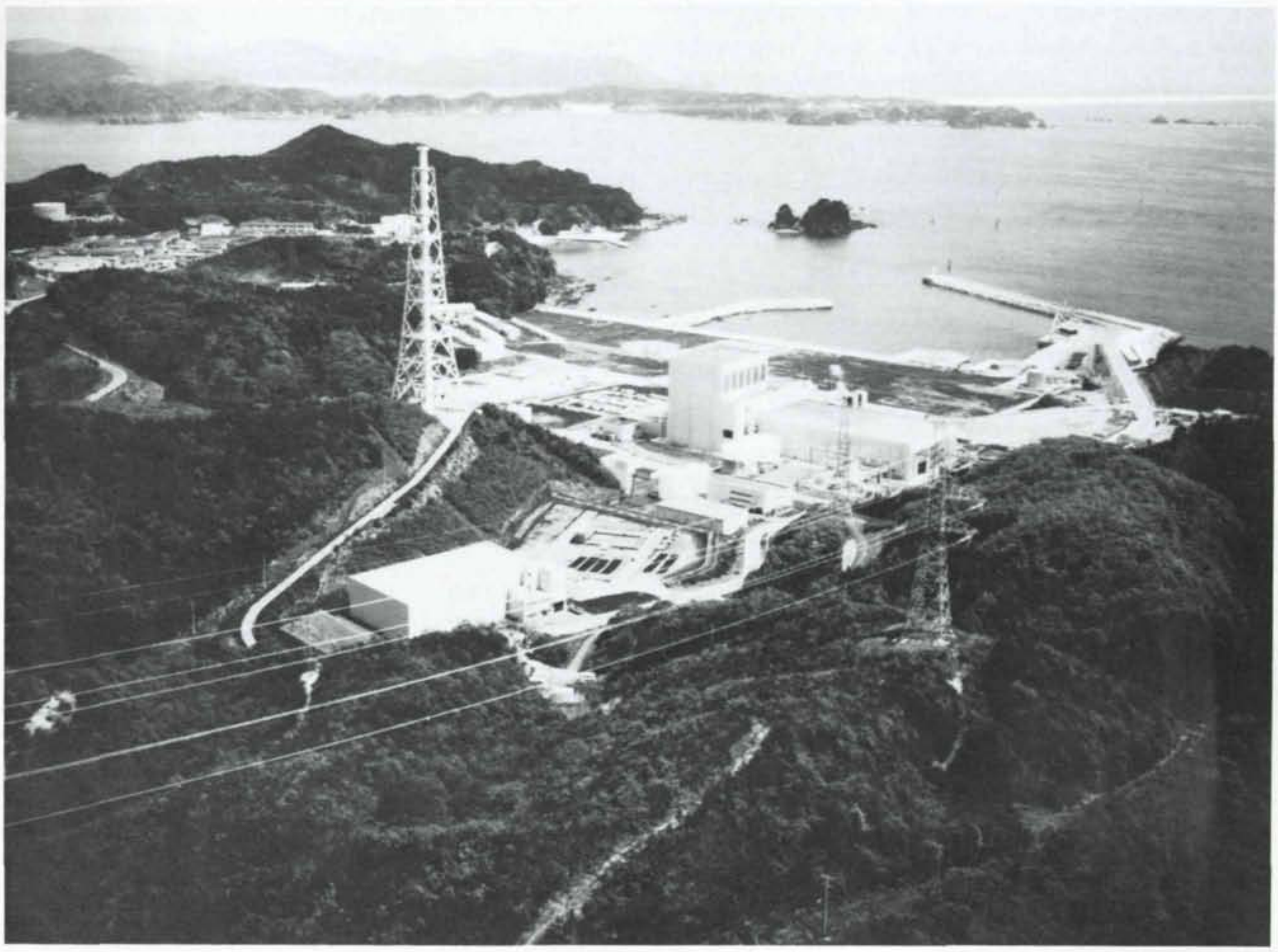
Mortality and morbidity estimates are somewhat uncertain because agreement is hard to achieve concerning the health effects of particulate and sulphur dioxide emissions from coal-fired plants and the risks to the general population that result from mishaps at nuclear power plants. According to Morris et al., oil- and gas-fuelled boilers that use current technology are somewhat safer than those that use coal or nuclear energy, and solar technologies are less safe because some solar cells use toxic materials, large structures must be built to gather the energy, and injuries are associated with maintaining the structures.[18]

Nuclear power, the physician, and society

The United States requires an adequate supply of electricity to run its businesses, light its homes and schools, air-condition its buildings, preserve its food, provide satisfactory medical care, and for many other purposes. Nuclear power is an option for generating electricity, as are coal, oil, gas, water, wind, and the sun. Nuclear energy also involves the production of ionizing radiation, which can adversely affect humans. Physicians should understand the principles of this means for generating power.

Experience indicates that if an emergency occurs in a nuclear power plant, physicians will receive inquiries from patients and their families, reporters, colleagues, and many others. Physicians should know how to find out how much radiation was released and be able to offer appropriate advice to patients and the public. Physicians should understand the signs, symptoms, and differential diagnosis of radiation injury and the importance of specific hematologic tests. (References 19 and 20 to this article should be available in offices, clinics, and emergency departments.) A difficult case may call for expert advice, which (in the USA) is available on a 24-hour basis from the Radiation Emergency Assistance Center/Training Site in Oak Ridge, Tennessee, Tel. 615/482-2441.

Physicians are viewed by the public as being knowledgeable and able to give informed advice regarding decisions and activities that involve health risks. They may be asked by community groups such as police



Onagawa nuclear plant, Japan.

and fire departments, radiation protection and emergency management agencies, hospitals, and industries to help plan for emergencies that involve radiation, chemical releases, fires, and natural disasters. If a disaster occurs, the Governor's office and state agencies probably will be involved, and assistance can be provided by federal agencies or programmes such as the Federal Emergency Management Agency, US Public Health Service, National Disaster Medical System, and the NRC. Most of these have regional offices in Boston, Mass; New York, NY; Philadelphia, Pa; Atlanta, Ga; Chicago, Ill; Dallas, Tex; Kansas City, Kan; Denver, Colo; San Francisco, Cal; and Seattle, Wash.

An additional need that physicians can help address concerns the role of science in society. All persons, including physicians, benefit from flourishing science and technology and suffer from languishing ones. To function optimally, members of a democratic society should have a reasonable understanding of scientific principles and concepts, which will help them make decisions about major issues such as nuclear power, chemicals in drinking water, hazardous wastes, pesticides, and food additives.

Many thoughtful persons believe that current US educational processes limit young people's understanding of science. Because of their leadership roles in the nation's communities, physicians can attempt to revise this limit by working to improve education for everyone in science and technology and their applications.

Recommendations

The Council on Scientific Affairs of the AMA recommends the following:

- **Need for electricity** — adequate capacity for generating electricity is necessary for people's health and the progress of society.

- **Energy conservation** — emphasis on the conservation and efficient use of energy should continue and accelerate.

- **Safety of generating electricity** — during recent decades in the United States, generating electricity has become increasingly safe and environmentally benign.

- **Safety of nuclear power** — generating electricity with nuclear power is acceptably safe in the United States.

● **Safety of reactors** — power reactors in the United States are designed and constructed for safe operation and for preventing unintended releases of radiation and radioactivity; reactor safety features have proved effective.

● **Workers' exposures** — exposures of workers to ionizing radiation have diminished during the past decade and are extremely low.

● **Disposal of radioactive wastes** — each state should continue its efforts to reach the goal of 1 January 1993, set by Congress for arranging disposal of low-level radioactive wastes.

● **Role of physicians** — physicians should have information available regarding how to treat persons injured by ionizing radiation. They have a broad responsibility to advise the public and respond to anxieties following a radiation emergency. Also, they should help improve public understanding of the benefits as well as the risks of nuclear power.

● **AMA's role** — the AMA should continue to monitor activities that affect the public's health and keep physicians appraised of technologies with implications for medical care.

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