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Nuclear Power and the Environment

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"Nuclear Power and the Environment"

Ecology has become a glamour word in recent years. We tend to forget, however, that it refers to the interrelations of a community of living things and their environment in the most complete sense -- the good and bad effects the environment has on the community and the good and bad effects the community has on the environment. To discuss nuclear power and the environment, then, we must look at those values of the community that are affected by nuclear power and consider which are enhanced and which diminished and to what extent. This prefatory remark is intended as a warning against the tendency of some critics of technology in general and nuclear power in particular to regard house-cleaning as the only proper function of the ecologist rather than just one of many concerns that must be part of the "community housekeeping" which ecology connotes.

What nuclear fission does for the community on the positive side is to provide a new source of energy to supplement the older resources, principally fossil fuels and water power. The energy of nuclear fission is currently being applied as heat to make steam to run turbines and generate electricity; but plans are well advanced to use the heat also for distillation of salty or brackish water in order to augment our diminishing water supply and to use steam from nuclear reactors in industrial processes and domestic heating. Other imaginative proposals include the use of what is now objectionable waste heat to prevent the undesired freezing of lakes and to enhance the productivity of farm lands by warm water irrigation.

The detrimental effects of nuclear power, actual or potential, are not all unique to nuclear plants. As for large power plants of any kind, nuclear plants involve large structures that many find esthetically objectionable, they use land that some may wish to see devoted to other purposes, and they require transmission lines that need broad and long rights-of-way, possibly through scenic or residential areas. In common with fossil fuel plants, they need large volumes of condenser cooling water and a means of disposing of the heat it absorbs.

Among the undesirable effects unique to nuclear power are:

1. The routine discharge of radioactive materials into the air and water at the power plant;

2. The shipment of intensely radioactive used nuclear fuel to a reprocessing plant;

3. The routine discharge of radioactive materials into the air and water at the reprocessing plant;

4. The long-term disposal of high-level radioactive wastes from the reprocessing plant;

5. The risk of a major accident at the power plant and a consequent large discharge of radioactive materials.

The rational course is to accept no undesirable effects unless there are equivalent benefits. The difficulty is that there are no units in common to determine such equivalence. A better approach to resolution of the problem may be possible through a comparison of alternative ways of obtaining similar benefits. We may then choose the way that has the least detrimental effect on that "community household" which is the subject of ecological concern, considering not only environmental effects but also such matters as availability of resources, dollar costs, and system reliability.

Alternatives to fission nuclear power that have been proposed include:

1. Expanded use of fossil fuel plants;
2. Expanded use of hydroelectric plants;
3. Prompt development and use of:
    a. Solar power;
    b. Geothermal sources;
    c. Tidal power;
    d. Wind;
    e. Fusion nuclear power.

Two temporary alternatives have been suggested, in order to postpone the need for a long-range solution and to make possible a so-called moratorium with respect to nuclear power development:

1. Take steps to reduce the community's use of electricity;
2. Increase the efficiency of electric generation by the use of magnetohydrodynamics (MHD) or other means.

The question to which this paper addresses itself is: How does nuclear fission power compare with the alternatives with respect to environmental effects? The national community must choose some solution of its power problem. Since that choice cannot be wisely made in a vacuum -- or even in the near-vacuum that admits only the narrowest environmental considerations -- "environment" must be interpreted in the broadest sense.

First, let us consider very briefly whether we can postpone the decision as to mode of power generation by reducing the use of electricity or by producing it more efficiently in existing plants. The consumption of electric power is determined by the most democratic process imaginable: every time you turn on a switch or buy an item of merchandise, you are casting a vote for electric power. A better educated electorate might vote for less power; but the increases in demand come largely from the less affluent members of society, who want what the affluent already have, and persuading them otherwise will be a very slow process. As for more efficient conversion of heat energy to electrical, the economic incentive hardly needs the supplement of environmental concerns to create pressure for its development. The research and engineering problems, however, are so complex that MHD promises no help for many years to come and so is no answer to the immediate need to choose tomorrow's power sources.

The crucial factor of time is sufficient to determine the answer with respect to other unusual sources of power insofar as the current problem is concerned, though most of the proposed sources have other shortcomings. Nuclear fusion is probably the most promising, but even the research barrier has not yet been surmounted: no one has yet been able to sustain controlled nuclear fusion in the laboratory. When and if that breakthrough is achieved -- and a "breakthrough," by its very nature, cannot be predicted -- a long period of engineering development must follow before commercial production arrives. The environmental problems of fusion power should be simpler to solve than those of fission power since radioactivity, except for radioactive hydrogen (tritium), will be a minor concern and the fusion process, with its high temperatures, should lend itself well to the application of MHD and so reduce thermal waste.

Solar power seems environmentally desirable, even though large areas would have to be dedicated to collection of solar energy. Desert areas might justifiably be sacrificed, but the problems of heat storage during nights and bad weather and of utilizing the theoretically high temperature possible from the sun -- the smaller the temperature range, the lower the efficiency for any heat conversion process -- remain to be solved, while the power losses and decrease of reliability with distance in power transmission tend to limit any future potential of this mode of power production to load centers within a few hundred miles of the heat collecting array. Geothermal power depends on the availability of sites with accessible heat and water, of which only a few are known. Deep drilling is believed by some to offer the promise of great expansion of this resource, but possible proof of that hypothesis lies in the future. The present geothermal sources present some environmental problems due to noxious gases and dissolved salts as well as noise, extravagant land use, and esthetic considerations; but the principal problem is the limited amount of exhaustible power that this resource is predicted to offer. Wind power is widely available but too variable and too diffuse to serve as a source of electrical power for an urban community. Tidal power is capable of economical development at only a few places where geography favors it by providing a basin where tides are high and the mouth of the basin is narrow.

Hydroelectric power represents about 1/6 of present electric generating capacity in the United States but is expected to decline in relative importance because of the limited number of sites that can be economically developed during a period when total generating capacity is predicted to double every decade. Though nonpolluting, hydroelectric power is not without serious environmental impacts, principally in the alteration of stream flow by dams and the flooding of land areas to create storage reservoirs. In some instances, the effects have been beneficial to the environment through control of floods and their damaging erosion; but, good or bad, the hydroelectric potential of the nation is too small to affect the immediate problem significantly.

The nation's choice, for the next several decades, must be between fossil fuel and nuclear fission.

Among the early objections raised by opponents of nuclear power, the hazards of routine radioactive effluents from the power plant were most emphasized. Though these are still a topic of debate, they no longer hold the forefront of attention. To understand the origin of the radioactivity discharged from a nuclear reactor, some acquaintance with nuclear processes is necessary as well as with the engineering design of present reactors. The fission process, which is the primary heat source of the system, depends on the fact that a neutron of sufficiently low energy will tend to seek out atoms of uranium-235 in a nuclear fuel that contains even a very small percentage of this isotope of uranium. The neutron enters the nucleus of that atom and causes it to split into two (or rarely three) parts and give off a large amount of energy. The products of the splitting are atoms of about half the 235-unit weight of the uranium atom plus about 2 or 3 neutrons of unit weight. The released neutrons must be reduced in energy in order to make them react preferentially with other U-235 atoms; this slowing down is accomplished in most present reactors by causing the neutrons to bump repeatedly into the hydrogen atoms of water molecules. On the average, at least one neutron from each fission must cause another fission or the chain will be broken and the process will stop.

The fractions of the split uranium atom, ranging from about one third to two thirds of its weight, constitute an array of different chemical elements, but each atom has too much energy to be stable. They give off this energy in a succession of steps, rapidly at first, in general, and then more gradually, changing from one element to another in this process of radioactive decay. Since each step has a definite probability of occurring in each kind of atom (each radionuclide or radioisotope), the rate of the process is commonly described in terms of the time in which the chance of changing is one half. That interval is called the half-life, since half the atoms in any group will change (disintegrate) in that time. The repeated halving process means that a given radionuclide will be reduced to one one-thousandth of its original amount in about 10 half-lives, to a millionth in 20 half-lives, and so on.

Another nuclear process of importance occurs when a neutron that has not been slowed down (moderated) meets an atom of uranium-238, the uranium isotope that forms 99.3% of natural uranium and generally more than 97% of the uranium in reactor fuel. The neutron tends to combine with the U-238 and, after some spontaneous changes, to yield plutonium-239, which is also fissionable by slow neutrons. Plutonium is expected to be one of the principal nuclear fuels of the near future, since the limited natural supply of U-235 must be augmented in some way if nuclear technology is to become an enduring source of power. A similar process of "breeding" nuclear fuel is possible and has been demonstrated by allowing surplus neutrons to react with thorium-232 instead of U-238, the product being another fissionable isotope of uranium, U-233. The plutonium "breeder" needs to avoid too much moderating of neutron energy in order to favor reaction of the neutrons with U-238, so it replaces the water moderator with a different coolant that does not contain hydrogen -- commonly, molten sodium. Though breeder reactors are being considered as the next advance in nuclear power generation, this paper concentrates on light water reactors (LWRs), which constitute the problem of the next decade or two, at least.

Since the usual fuel in the LWR is in the form of sintered cylindrical pellets of uranium oxide, a ceramic material, the atom-by-atom splitting produces atoms of radioactive materials dispersed throughout the ceramic mass. The first few radioactive transformations after fission are so rapid that the products cannot migrate very far; but longer-lived gaseous radionuclides can move out of the fuel into the space in which it is contained. The pellets, about a half inch in diameter, are assembled in sealed tubes of either stainless steel or a zirconium alloy (zircaloy), about 12 feet long in typical reactors. In spite of careful manufacture and inspection, pinhole leaks may develop in some of these tubes, of which a commercial reactor may contain, say, 40,000. The gases may then escape from the leaky tubes into the coolant. What happens then depends on the type of reactor.

Two types of LWR are in use: the boiling water reactor (BWR) and the pressurized water reactor(PWR). In the BWR, the coolant is allowed to boil and form steam as it flows past the hot fuel tubes. This steam goes directly to the turbine that drives the generator. After expending most of its energy in the turbine, the exhaust steam goes to a condenser to be converted to hot water which is pumped back into the reactor in this closed cycle. But the cycle is not fully closed. In addition to small amounts of leakage at packings of shafts and valve stems, for example, there is a major normal path for routine release of noncondensible gases.

As previously noted, a heat engine's efficiency depends on the range of temperature over which it operates. To lower the temperature at the turbine exhaust, it is desirable to maintain as low a temperature as practicable in the condenser. When this is done, the water vapor pressure is below atmospheric pressure; but then the pressure of dissolved air or other gases becomes significant and spoils the vacuum that cooling is intended to produce. So air ejectors are required. They eject not only air but also the radioactive krypton and xenon isotopes that leaked from the fuel. Because of the relative amounts produced in fission, the energies of their radioactive emissions, and their half-lives, Kr-85, with a 10-year half-life, turns out to be the most important of these from a long-term hazard viewpoint. Both krypton and xenon, members of the "noble gas" series, are chemically inert, so the hazard arises only from the beta radiation they emit as they diffuse through the air when discharged from the power plant stack. BWRs generally use tall stacks to insure wide diffusion and dilution of these gases before they reach the vicinity of people. Licensing rules also require that reactor sites establish exclusion areas under the control of the licensee and demonstrate low population densities nearby, in order to minimize these and other risks. The technical specifications that form an essential part of construction permits and operating licenses limit the average amounts of these radioactive gases that may be discharged, and measurements have shown that these limits have not been exceeded in existing plants and, in general, have not been closely approached. A tabulation of gaseous releases from all power reactors in 1967 and 1968 (1) showed that the BWRs discharged from 1 to 57% of the permissible amounts. The exceptional high value pertained to a plant that was deliberately continued in operation to study the behavior of defective fuel rod cladding of one particular type.

There is another volatile radionuclide that is of special concern because of its biological behavior. Iodine is an essential component of the thyroid hormone and is of so little abundance that it is seized upon by the thyroid gland, where it is concentrated in a small volume of tissue. If it happens to be a radioisotope of iodine, its radiations are believed to increase the risk of thyroid cancer. Direct inhalation of radioactive iodine, even in case of gross emission hundreds of times the allowable amount, is a minor consideration compared to the contamination of pasture grass and other cattle feed. The large amount of feed a cow consumes to produce a few gallons of milk, into which she introduces much of her body iodine for the nourishment of her calf, creates a concentration mechanism for radioactive iodine. For this reason, standards for allowable concentrations of radioiodine are set at far lower values than the direct effect would require, and special precautions have to be taken to eliminate iodine from reactor effluent gas. These measures have proved effective, as shown by the continual surveillance of the environs of nuclear reactors. One very detailed study (2) by the Public Health Service around the Dresden reactor of Commonwealth Edison Company reported that "no iodine-131 was found" in milk from a neighboring farm in the downwind direction even though typical amounts of I-131 were being emitted from the stack and traces corresponding to about 1/100 of acceptable level were found in cattle thyroids.

The PWR uses a pressurizing system to prevent the coolant from boiling in the reactor. The hot water flows in a closed cycle through steam generators in which heat is transferredto a second closed system, where the water boils to produce steam for turbine operation. The gaseous fission products thus do not become involved in turbine and condenser operation, and trifling amounts of radioactive gases are discharged in normal operation (1).

The same fission process that occurs in the nuclear fuel will occur in any traces of fissionable material that occur on the outside of fuel rods or in the coolant. It must be remembered that the actual mass associated with a large amount of radioactivity may be almost inconceivably small. A trillion microcuries of iodine-131, for example -- 50 billion times the amount used in many thyroid tests -- weighs only 8 grams or about a quarter of an ounce, and many other radionuclides have an even higher ratio of activity to weight. Still another source of radioactivity in the coolant arises from the process of neutron activation. When one of the neutrons moving through the coolant encounters some atom of dissolved material that may have come from the reactor materials or from the original feedwater, it may combine with that atom and change it from a stable to an unstable isotope of that element. All of these radioactive atoms in the coolant are undesirable, and procedures to remove them are part of the system. For the most part, they are transferred by ion exchange systems (similar in action to water softeners) to resins that become one of the solid radioactive wastes requiring disposal.

Neither liquid nor solid radioactive wastes are discharged as an inherent part of the process in the way the radioactive noble gases are released from the BWR. The liquid wastes that arise from necessary discharges of coolant are contained in a closed system, just as the solid wastes are in the demineralizing resins. The radioactive concentrations are comparatively low, so the liquid wastes may either be concentrated and, together with the solids and solidifying agents, shipped to one of a few licensed land burial sites, or they may be enormously diluted by feeding them into the cooling water stream that leaves the condenser. Since the latter practice requires careful measurement of the amount of activity before discharge, the controlled concentration in the water discharged to ocean, lake, or river is kept at or below drinking water standards. The effects of such discharge into an aqueous environment must be monitored to insure against unexpected build-up in plant or animal organisms. Studies of these effects around existing nuclear plants show no significant adverse consequences.

It may be well to digress at this point to consider the controversy over the significance of the low levels of public exposure accompanying routine reactor operations. The history of formal radiation standards goes back more than 40 years, though statutory regulation of exposures dates from World War II. The scientific basis of the standards is a composite of thousands of studies by hundreds of investigators worldwide, reviewed continuously by national and international committees. The Internation Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) are probably the most important of these bodies, though the Committee on the Biological Effects of Atomic Radiation (BEAR Committee) of the National Academy of Sciences had a very significant input some 15 years ago. These groups have published many reports over the years and continue to do so. When the United States Atomic Energy Commission was established in 1946 (3), it was charged with the duty of protecting people from the harmful effects of atomic energy while advancing its technical development. The AEC then and since has based its regulatory standards on the standards recommended by these scientific bodies.

A higher echelon of governance of radiation exposure was established in

1959 with the creation of the Federal Radiation Council (FRC), first by executive order (4) and then by statute (5). This was a cabinet-level policy-making body for federal activities involving radiation, and although its duties have been transferred to the Environmental Protection Agency (EPA), established in accordance with the President's Reorganization Plan No. 3 of 1970 (6), FRC policies have been maintained by EPA. The FRC, utilizing in-house talent of its members' departments and outside consultants to review the recommendations of the scientific bodies previously mentioned, proposed Radiation Protection Guides (RPGs) and Protective Action Guides (PAGs) (7) that were deemed to afford a degree of public protection more than sufficient to keep the risks commensurate with the benefits of the many applications of nuclear and atomic energy. They continued the practice of all the scientific bodies and the AEC with respect to medical uses of radiation and radioactive materials; they kept hands off. This attitude arose primarily from the view that the individual patient is the beneficiary and his risk can be settled between himself and his physician or dentist; but with more recent scientific concern over the socially important genetic effects of radiation, medical exposure, too, is tending to become a policy concern of government.

The FRC confirmed the occupational exposure standards of the AEC as suitable guides for peaceful uses of atomic energy but added new criteria for acceptable exposure of the general public. The radiation worker is considered reasonably well protected if the average exposure of the most sensitive organs, determined in specified ways, is limited to 5 rem (5,000 millirem or mr) per year after he reaches the age of 18. Radiation workers under 18 and the general public are to be kept to a limit of 500 mr per year as a guide level. The policy is to stay as far below these guide levels as is economically practicable and to consider causes and cures if the guide level is approached or exceeded, recognizing that a short period of excess is unimportant if the average can be kept low. Since it is impracticable to monitor everyone among the public, a technique was presented by which to assure the likelihood that no one gets more than 500 mr per year. If conditions in the environment due to radiation-causing activities are such as to maintain the average exposure of "a suitable sample of the exposed population" (undefined) (8) below 170 mr per year, it is permissible to assume that no one in that sample gets more than 3 times as much, or 500 mr per year. The exposure levels of the guides refer to the composite of all causes of exposure other than natural background radiation (about 100-125 mr per year typically (9)), medical and dental radiation (causing an average of 35-55 mr per year of genetically significant exposure in the United States (10,11), and military weapons tests of any nation. There are technical difficulties in combining the effects of whole-body external irradiation and radiation from materials taken into the body, but the numbers used here are generally employed without further refinement.

Critics of nuclear power have attempted to calculate its effects on the assumption that it will produce an average exposure of everyone in the United States to 170 mr per year from birth to death. That assumption is at odds with the facts that existing plants produce exposures of the order of 5 mr/yr or less at the plant boundary (12) and then only in the most critical direction, and that averages of exposure over areas of, say, 50 miles radius are typically about 1,000 times smaller (13). Estimates of the expected dose to the United States population from an array of reactors spaced 30 to 50 miles apart indicate that the average would be less than 1 mr/yr (13). This estimate is consistent with those of several other experts cited by the same author. There is reason to believe that future practices will, in fact, be constrained within even tighter boundaries. Since the policy established by the FRC in 1960 has required that exposure be kept "as far below this guide as practicable" (8), the AEC has finally yielded to the nuclear industry's criticism that this is not a specification to which an engineer can design and has proposed a numerical value applicable to LWRs. Enough experience has been accumulated with power plants of this kind to show that it is indeed "practicable" economically to limit individual exposure in the vicinty to 5 mr/yr, since existing LWR plants have been meeting this requirement.

The controversy over the biological effects of 170 mr/yr exposure for 30 years or more is not as easily resolved. Critics of the standards assert that the 5,000 mr accumulated in the first 30 years of life, if everyone is exposed continually to the maximum population dose, will produce the same effect as if the same dose were administered in a single exposure. No studies have been or could be conducted to produce meaningful results at such low dose rates because the phenomena to be observed -- cancer or genetic mutations -- occur naturally at rates so large and so variable as to obscure the possible effects of a small amount of added radiation. For that reason, our inferences as to effects have to be based on some hypothesis related to observations at much higher doses and enormously higher dose rates.

Genetic studies involving millions of mice (to get a valid statistical base for the small effects expected) have shown that dose rate makes a marked difference in mutation response in these animals (14). At low dose rates -- still about 30,000 times the dose rate of 170 mr/yr -- genetic mutation effects, observable in both males and females at high dose rates, were undetectible in females and were reduced by a factor of more than 3 in males. There is no clear basis for interpreting the meaning of this result in human genetics, since it is not known whether man is more, less, or equally subject to mutation and especially because what little is known of the long-range effects of mutation in a non-inbred population tends to contradict theoretical predictions of harm to the population as a whole (15).

With respect to carcinogenic effects of radiation, both in experimental animals and in man, all of the available data involve very much higher dose rates than for genetic effects -- up to billions of times the dose rate of 170 mr/yr -- and, except for one unique block of human data, the total doses are vastly greater than the 30-year total at 170 mr/yr. The one set of data that indicates a significant carcinogenic effect from doses of the order of a few rem administered at high rates relates to irradiation of the human embryo. This continuing study of effects on the offspring of British mothers X-rayed during pregnancy (16) must be interpreted with caution when estimating the effects of irradiation after birth, since the embryo is known to be unusually sensitive to various disturbing factors, including chemical agents and radiation, during its rapid development.

The most pessimistic estimates of carcinogenic effect are based on another questionable assumption in addition to the unproved hypothesis that a slowly accumulated dose of radiation is as effective as a sudden dose of the same size. The assumption is that any radiation received at any age contributes a lifelong multiplying factor for the incidence of all forms of cancer. The ICRP, in a recent report (17), concluded with respect to this assumption that "a survey of the available evidence did not confirm its validity" and that "the proper measure of carcinogenicity for the purposes of radiation protection is the number of addidtional cases of induced cancer...." Their survey of all the available human data -- from persons irradiated for therapeutic reasons either as children or as adults, the Japanese exposed to atomic bomb explosions, physicians occupationally exposed in their practice, and fetuses irradiated in examinations of their mothers -- led to no clearly quantitative conclusion from which a cost in human suffering could be derived. Risks of incidence of various types of cancer ranged from a low, for many body organs, of "about one case per million per rad or less for high dose-rate exposures" (a rad is about the same as a rem or 1,000 mr) to "a few cases per 100,000 per rad for high dose-rate exposures" of the two most sensitive organs, the bone marrow and the thyroid gland. They noted, however, that some types of cancer seldom prove fatal, that certain types occur most commonly at certain times of life, and that there is no known way of measuring "equivalent harm."

It is interesting to compute the calculated effect of nuclear power on cancer incidence in the United States if the unproved adverse hypotheses of the most severe critcs regarding carcinogenic effects of radiation are nevertheless applied to some realistic estimates of radiation exposure due to nuclear power. Assume that the average dose in the United States after 2 or 3 decades of nuclear power plant construction reaches the higher levels previously cited (13), namely, 1 mr/yr. Since the analysis to which reference has been made came to the conclusion that 32,000 additional cancer deaths per year would be caused by an average exposure of 170 mr/yr for 30 years, it follows that about 200 additional deaths would result from 1 mr/yr for 30 years. Assuming no change in population size, it means that, starting some 5 years or so beyond a 30-year interval following attainment of the estimated level of exposure (that is, some 50 years from now), a slow rise in cancer incidence would raise the usual number of cancer deaths from about 320,000 per year (18) to about 320,200. And, since the cited value is obtained by applying a multiplying factor to the observed incidence of all forms of cancer, these theoretical deaths would occur among the elderly, for cancer is characteristically a disease of old age. More than half of all cancer deaths occur above the age of 67 (18). If a change of this size were actually to occur, it would be undetectible in the random variations of cancer incidence.

Returning to the question of nuclear power's environmental impact, the shipment of irradiated fuel from reactors to reprocessing plants must be considered. After a reactor has operated for months on its original charge of fuel, certain fission products that tend to capture neutrons, and thus waste them, build up to uneconomic levels in the fuel. Fuel rods in the most active locations are most affected, so the usual practice is to remove one third of the fuel assemblies each year or so, shift the others to more active regions of the core, and add fresh fuel. The irradiated fuel, containing more than 90% of its original fuel value plus large amounts of radioactivity, is stored in a water-filled pool for 3 or 4 months to allow the radionuclides of shorter half-life to decay, thus reducing the total activity to some 20% of what it was initially (19). The assemblies are then loaded, under water, into specially designed shipping casks for transportation to a reprocessing facility. The remaining radioactivity still generates enough heat so that provisions for heat removal are essential, and the external radiation levels must be kept down to allowed limits by heavy shielding, so that the shipping casks are large and heavy devices, ranging from 20 to 100 tons. They are required to withstand a series of rigorous tests, including a 30-foot drop onto a hard surface, a penetration test, an intense fire, and submersion.

Movement of such loads by train or truck involves the risk of accidents of varying degrees of severity. Studies of the risk have been ongoing for more than 15 years, using the techniques of operations research and the actuarial methods of the insurance industry (e.g., 20). Although theoretical conclusions may be reached as to dollar value of the risk for any particular shipment by a specified means over a designated route, many other variables still affect the result; and, whatever the result, it remains of limited applicability. The premium rates established 15 years ago by the Nuclear Energy Liability Insurance Association (NELIA) for truck shipments of irradiated fuel elements represent some kind of educated guess as to the risk. They offered to cover the first million dollars of liability at $25 per loaded day, with graduated premiums down to $2.50 per million for coverage above $10 million, up to their then limit of $60 million (21). As with reactor insurance, they agreed to adjust premiums downward after each 10 years of experience. Though data are not at hand with respect to this type of insurance (which may never have been sold, in view of the coverage maintained by reactor operators under the Price-Anderson Act), the experience with reactor insurance has led to annual refunds of premium since the first 10-year interval was reached in 1967. The refunds in 1971 represented 68% of the premiums paid in 1961 (22). At $2.50 per million (before refund), the NELIA estimate of likelihood of a truly catastrophic accident was apparently less than 1 in 400,000 per day of loaded travel. As of February 15, 1965, the AEC reported that the only claim ever filed in connection with reactor insurance was for $3,500 to clean up two trucks contaminated by a liquid spill (23). It may -- and hopefully will -- be years before probability values can be established through the customary actuarial procedure of relating numbers and severity of occurrences to opportunities for occurrence of the hazard insured against.

At the reprocessing plant, the irradiated fuel is cut up and chemically dissolved in order to recover the large fraction of unconsumed uranium fuel and the plutonium that is formed to varying degrees even in a nonbreeding reactor. ("Breeding" implies making more fuel than is consumed; but "conversion," which occurs when the "breeding ratio" is less than 100%, takes place in all LWRs.) In the solution process, the gaseous fission products are released into the reaction chamber. The current practice is to discharge these gases into the air, since the concentrations produced at the plant boundary are well within prescribed limits. In the course of time, that practice will undoubtedly have to be changed, and perhaps the change should be introduced promptly, without awaiting any real necessity, in order to conform to the principle of "as low as practicable." The techniques have been developed.

Only one place in the United States is presently engaged in reprocessing irradiated fuel commercially, and it is located in the middle of a 3500-acre tract set aside as a nuclear industry center near Buffalo, New York. Another plant, at Morris, Illinois, is scheduled for early operation, and one at

Barnwell, South Carolina, is under construction. Krypton-85 is the only gaseous fission product present in significant amount at the time of reprocessing, under current practices. An AEC report (24) states that "present environmental concentrations result in a dose to man which is less than 0.1 per cent of the background dose..." from natural sources -- in other words, less than 0.1 mr/yr. "The AEC and the U.S. Public Health Service have recently completed studies... [which] indicate that even though present plant design and operating methods are used through the year 2000, radiation exposures to the general public resulting from the release and worldwide dispersion of krypton will not exceed approximately 1 per cent of the radiation protection guides..." or 5 mr/yr to any individual.

Iodine-131, which is a solid at ambient temperatures and which forms many compounds, almost all of which are far less volatile, may nevertheless appear in the off-gases unless special precautions are taken. It has a half-life of only 8 days, so its total quantity will have been reduced by a factor of about 30,000 in the interval between removal of the fuel from the reactor and its chemical treatment; but the hundreds of megacuries of fission products present in a large reactor after prolonged operation may include megacurie amounts of I-131. Measurements (25) at the only commercial reprocessing plant show that only 5 to 10% of the iodine in the fuel reaches the stack and that scrubbers there remove most of that. Another isotope of iodine, I-129, though present in far smaller amounts than I-131 (about 10 microcuries per megawatt-year of reactor operation -- a megacurie is a trillion microcuries), has to be considered also. It has a half-life of about 20 million years, so it persists virtually forever. The long half-life means that it takes a much greater mass of this material to constitute a given amount of radioactivity, so it would be difficult for people to get much exposure from this source, even if it were widely dispersed. Good practice will require its removal and inclusion in the high-level liquid wastes that accumulate at the reprocessing plant.

The liquid wastes from a fuel reprocessing plant present a very different problem from that associated with the liquid wastes that occur at a reactor installation. The radioactivity per unit volume of the solutions of irradiated fuel after removal of uranium, plutonium, and any other useful materials is much too high to consider dilution and discharge to a place accessible to the public. The temporary expedient that was begun during World War II and is largely still in use is to store these solutions in stainless steel tanks. Other methods of confining and storing this material have been developed over the years and applied in limited trials. Conversion to solid forms is common to almost all proposed methods.

Of the tens of millions of gallons of liquid waste produced in AEC installations, some 41 million gallons have been concentrated and solidified right in the storage tanks at Hanford, Washington (26). Another 2 million gallons -- half the total produced -- have been converted to granular solids by calcining at the National Reactor Testing Station in Idaho (27). One of the promising methods that has been field-tested on a small scale is the mixing of the liquids with cement and injection of this grout between layers of shale in deep underground formations. Even more promising is the conversion of the solidified wastes, with added ingredients, into glass and ceramic types of solids that can be stored in cans in a suitable place.

Vitreous and ceramic materials, incorporating the kinds of radioactive materials expected in wastes, have been prepared and studied for over 16 years (28). Tests of solubility and resistance to prolonged irradiation showed that materials of this kind can be made durable enough to last thousands of years with extremely small loss of their radioactive content even if immersed in water. Plans proposed for the storage of such materials nevertheless contemplate seeking assured dry spaces, especially because there may some day be good reasons for retrieval of some or all of these substances. Concrete vaults or caverns in deep rock have been proposed for use, as also hollows blasted out deep underground by nuclear explosives; but the favored kind of site among the experts is a salt deposit, especially an abandoned salt mine. A salt deposit has several inherently desirable characteristics: It is structurally strong and stable, its very presence indicates an absence of groundwater at the site through geologic ages, it is a good conductor of the heat that radioactive materials generate, it is not changed in characteristics by prolonged irradiation, and it is just plastic enough to seal any cracks that might be made in its structure by seismic forces (29). Such sites have been safely used for years as storage reservoirs for liquefied petroleum gas (30). There is a tremendous area of known salt deposits in the United States (31), much of it at suitable depths to provide economical access and adequate earth cover. In its first undertaking to make a field trial of this method, the AEC made an unwise choice of site that has led to much unfavorable publicity, misdirected at the basic concept. The concept, however, apparently remains valid and a better site for its application is likely to be chosen in the near future.

Critics have stated that such sites would have to be guarded for 24,000 years, choosing that number because it is the half-life of plutonium-239, the most important isotope of that element for nuclear power. Aside from the fact that very little plutonium would be allowed to go to waste, it is clear that half-life is a poor indicator of hazard. Iodine-131, with its 8-day half-life, is a much more hazardous material than I-129, with a 20-million-year half-life, just because of that difference. The fact is that a burial site for high-level wastes must be deemed just as permanently out of bounds as the radioactive molten core of the earth, to be approached only by experts for specific reasons and by sophisticated methods. Once a site is considered full and is sealed in, it is expected to require no attention.

The principal focus of criticism of nuclear power at present seems to be the risk of catastrophic accident in a reactor that might contaminate a large area and create environmental radioactivity levels sufficient to cause many deaths. Assessing this risk involves the difficulty previously noted, that the ratio of the number of occurrences of the injurious event to the "exposure" or opportunities for occurrence is still zero. Redundancy -- the use of replicated systems to sense and control undesired conditions -- is the rule in nuclear power plant design; but the possibility of concurrent failure can never be completely eliminated, even though its probability can be made extremely low. The safety of a nuclear power station rests on the inherent safety characteristics of the reactor itself; the safeguards of instrumentation, control, containment, and the like that are added in the engineering design; the general administrative controls and the caliber of the personnel through whom they are applied to minimize the possibility of accidents and to limit the harmful effects of any accident that may occur; and the detailed procedural safeguards that insure that each of these aspects is thoroughly checked, both initially and throughout the lifetime of the plant.

The only foreseeable mechanism for release of large amounts of fission products within the reactor vessel is the melting of fuel rods because of excessive heat. The probable consequences of such an event will be discussed shortly; how it may occur must first be considered. The inherent characteristics of LWRs together with their added safety features do indeed make the probability of extensive fuel melting virtually zero so long as water is maintained in the core. The only process that might result in a serious meltdown appears to be a total loss of coolant -- the loss-of-coolant accident is abbreviated to LOCA. Since there are multiple pumps, multiple power sources for the pumps, multiple water resources, and multiple paths from pumps to reactor in the typical design, safety analyses for the worst case postulate a double-ended break in a feed line large enough to let the hot water under pressure escape and flash into steam at a rate too great for the other pumps to overcome. The nuclear fission process shuts down automatically because, without the moderating action of the water, neutrons of the proper energy to sustain the chain reaction are too few. The heat generated by the fission products, however, continues to pour forth, though at a rate which diminishes rapidly in the first few minutes and more slowly for weeks and months thereafter. If none of that heat could escape, it would begin to melt fuel rods in seconds; so reactor designs since 1968 have been required to provide some type of emergency core cooling system (ECCS), though some manufacturers chose to include an ECCS years before it became a prerequisite for a license.

The likelihood of a LOCA evidently depends on the likelihood of a break of the postulated size in the high pressure system. No numerical measure of that risk is available, but there is a body of data pertaining to it. To point to the nonoccurrence of such an accident in the hundreds of reactor-years of experience with central power station and naval reactors is only mildly reassuring as a statistic. It is proper to add to that our knowledge of high-pressure steam experience in fossil fuel plants and the relative characteristics of these two types of system. In response to a query, the chairman of the Uniform Boiler and Pressure Vessel Laws Society wrote (32) to endorse the concept of "comparing the reactor design and its postulated failure to that of high pressure boilers with their associated piping. Above 600 psi [pounds per square inch] operating pressure, there have been no incidents of major (catastrophic) failures such as a vessel rupture or a steam line parting. The serious boiler accidents that do occur are in the low pressure range where operation has been the cause, not the design.

"In high pressure boiler experience, the controls, operating personnel, safety devices, instrumentation, etc. are all designed with sophisticated knowledge and maintained to assure the intended safety and reliability. Safety has been 100% established because of the universal requirement of ASME [American Society of Mechanical Engineers] construction and the millions of hours of operating experience. Today the goal is far beyond safety. It is reliability, the prevention of minor failures that shut a boiler down with the resultant economic losses."

Some further excerpts are: "There are many symptoms that provide ample warning of an impending failure. Material deterioration may be monitored, leaks may be detected, operating performance goes out of balance." And he repeats: "...the Insurance Companies report no major boiler or piping failures above 600 psi." The level of 600 pounds per square inch and upwards includes all central station boilers constructed since about 1930.

The factors that have made these systems safe through thousands of cumulative boiler-years of operation are augmented in nuclear power plant design and practice. The ASME Code has been made more rigorous when applied to nuclear systems, thereby establishing greater factors of safety. Not only do the manufacturer and the operating utility inspect design and construction but also an independent and critical official agency, the AEC, which subjects the design to detailed review by its staff and by an independent body of experts, the Advisory Committee on Reactor Safeguards, and which conducts continuing inspections from the earliest stages of construction throughout the lifetime of the plant. Their findings have to be aired before the public in documents and in administrative hearings. The applicant for a license must demonstrate that it has an adequate quality assurance program and qualified personnel, who must themselves pass licensing examinations. The physical structure of the reactor, which starts out stronger because of the stricter code requirements and more rigorous inspection, is likely to remain stronger because it is not subjected to the corrosive action of products of combustion, since the heat is delivered internally to the water. There is a deteriorative action of radiation on metals that tends to make them brittle in the course of time; to verify that this process is not proceeding faster than predicted from tests, samples of the vessel's material are placed inside the reactor where the neutron flux is greater than in the vessel's walls and are removed for testing on a specified schedule (after 1, 3, 5, and 10 years in a typical current reactor). The more extensive instrumentation in nuclear plants and the extreme sensitivity of radiation detecting instruments make early discovery of minor failures even more probable than in fossil fuel plants. To add one more point, it is likely that nuclear plants will carry the base load of the system in which they operate, since their special advantage is low fuel cost per kilowatt-hour; thus, they would avoid undesirable rapid fluctuations of load.

None of this discussion is intended to imply that the risk of a LOCA is zero; merely that it is extremely small. The last line of defense to prevent a meltdown if a LOCA does occur is the ECCS, and that is presently a storm center of controversy. At the time of writing, the elaborate public hearings on effectiveness of these systems have continued with only minor pauses since January, 1972. The subject is too complex for detailed discussion here, but a sketchy outline may be appropriate. As noted, some type of ECCS has been required in order to meet licensing requirements in recent years, and a program has been instituted to require backfitting of such a system in older reactors. Though tests of these systems have been conducted, the conditions did not correspond to those of a real reactor system failure; behavior in the LOCA case has been computed from the test data. In some small-scale tests reported in 1971, results were at the very least "anomalous" (33) and suggested the possibility that some of the ECCS designs might not work as intended. It would be rash to predict the outcome of the present hearings; but it is safe to say that further tests, and probably on a scale more nearly approximating reactor sizes and operating conditons, will be conducted in the near future. As an interim measure, the AEC has prescribed limitations on operation that will increase the safety margins against meltdown even if all the multiple cooling systems fail simultaneously.

The consequences of a fuel meltdown are uncertain. Some have visualized what has been called "the China syndrome," in which the fuel all melts and forms a pool at the bottom of the reactor vessel, melts through the vessel wall and on through other structures and the concrete foundation into the ground beneath, where it continues its downward path, not quite to China but to a depth of perhaps a few thousand feet in a month or so. It is not at all clear that large amounts of radioactivity would necessarily be widely dispersed even under these conditions, since reactors are housed in containment structures designed to hold the steam, gases, and volatile materials from a LOCA, and a total meltdown may not make the interior conditions exceed the capabilities of the system. Indeed, self-burial of the radioactive materials at great depth might be a boon. No speculation as to the possible effects can have any meaning unless it concerns a specific design and defined conditions; but these prerequisites for analysis have not been apparent in any of the material that has come to my attention. The tests that initiated the crisis situation were said to represent the PWR case, and BWR proponents claim that their situation is entirely different.

From many tests involving deliberate melting of irradiated fuel and a few instances of accidental meltdown in experimental reactors, it is known that, even without specially designed containment, most of the fission products "plate out" on any available surface. In a discussion of release of fission products from experimentally heated uranium dioxide, for example, the AEC reported:

"The most rapid release is found on fuel melting, when large fractional releases of many fission products occur within a few seconds' time. Fortunately, many of these plate-out (particulates which precipitate and are deposited on the vessel wall) even on surfaces above 1,000°C [1,830°F.]. The data indicate that less than one percent of the strontium, zirconium, cerium, barium, and uranium oxide are released from the 'high-temperature zone' (1,000°C.) to cooler portions of the experimental assembly." (34)

In the accidental destruction of a small, experimental, military reactor through operator error in 1961, much of the fuel was melted down. This was a metallic uranium fuel, which could not retain fission products as the ceramic uranium oxide fuel does. Cover plates on the reactor head were open, and the reactor core was violently shattered. The reactor was not enclosed in a safety containment, as the central station power reactors are, but was housed in an unsealed, corrugated metal shed. Nevertheless, except for the escaping portions of the iodines and noble gases, estimated at 100 to 200 curies total or approximately 0.01 to 0.02% of the fission product inventory, something less than 5% of the total activity is estimated to have escaped from the core into the building, and only about one millionth or less of the fission products present in the reactor is estimated to have reached the surrounding area (36).

To attempt, as some have done, a calculation of numbers of deaths and injuries and a dollar estimate of property damage from the release of radioactive materials to the environment as a result of an accident so poorly defined and of such low probability of occurrence seems an unprofitable undertaking. Added to all the other uncertainities are those of undefined accident conditions relating to weather, population distribution, times and distances, direction of wind, and human behavior, among other things. Suffice it to say that all those knowledgeable in such matters agree that the extensive dispersion of a large amount of radioactive material in a heavily populated area would be a major calamity, but not on a scale markedly different from other potential accidents. An interesting study of that question appears in some material that Congress considered when reviewing the atomic energy indemnity program (35). The present siting practice for nuclear reactorsis designed to insure that, if the almost impossible were to happen, the numbers of people who might be too close to escape would be relatively small. But the chief reliance of those who support nuclear power development rests on the vanishingly small probability that the catastrophic event will ever occur -- accident, yes, but not the "China syndrome."

There seems to be a natural reluctance to accept a small chance of harming a lot of people as the equivalent of a large chance of harming a few. A continuing one-in-a-million chance of killing 1,000 people seems much worse than a continuing one-in-a-thousand chance of killing any one person in that thousand, even though, to an insurance actuary, the ultimate risk may be mathematically the same. Fossil fuel power is known to involve many and serious environmental costs, including loss of many lives; but its costs are not the dramatic killing of tens of thousands that some of nuclear power's critics visualize. Rather, the costs are paid in little bits and pieces -- a few miners here, a few people killed by the thousands of coal cars that are already required at present power levels, a few people asphyxiated by gas or killed by burning fossil fuels in closed spaces, a larger number by fires started by fossil fuel use, seldom the 170 or so that died in a smog episode in New York City in 1966 (37) or the 3500 to 4000 deaths attributed to a smog episode in London in 1952 (37). There has been no study of the long-range effects of fossil fuel chemical pollution in any way comparable with the numerous studies of radiation hazards; but even the radioactive discharges from plants using our most abundant fossil fuel, coal, have proved at least equal in hazard to those from our least offending nuclear plants (38), and other studies (e.g., 39) have noted the presence of many known chemical carcinogens in the pollutants resulting from fossil fuel combustion.

In other aspects of environmental impact, nuclear power has both plusses and minuses as compared with fossil fuel. A disadvantage of present nuclear plants that has received much attention is the greater amount of waste heat they must dispose of, as compared with fossil fuel plants. It was noted earlier that the heat in the steam is used more efficiently as the working temperature range is increased. For that reason, fossil fuel plants superheat the steam -- the steam is given an extra shot of heat after it leaves the boiling water. LWRs have not been able to do that; an experimental nuclear superheating plant in Puerto Rico was unsuccessful. The result is that the best fossil fuel plants today have about 40% net thermal efficiency while the LWRs operate at about 32%. It is expected that other reactor designs -- the high temperature gas-cooled reactor (HTGR), one of which is in operation and another near that stage, and the liquid metal fast breeder reactor (LMFBR), development of which is being pressed -- will reach 39-43% efficiency; but, for the present, the nuclear plant wastes about 68% of its heat and the best fossil fuel plants about 60% (plus about 10% in the stack gases). The difference is greater than 68:60 since the nuclear plant must have a 25% greater input to get the same electrical output. The net effect is that the cooling water carries about 40% more heat away from the condenser of a nuclear plant than from a fossil fuel plant of the same electrical capacity.

If that heated water (typically 15-20°F. hotter than when it entered) is discharged into ocean, lake, or river, some problems arise that are discussed in a companion paper by Donald L. Lollock. The heated water need not be handled in that way (called once-through cooling), but alternatives cost more. If space and climatic conditions permit, it may be delivered to a cooling pond, where evaporation transfers the heat, plus water vapor, to the air and the water is eventually recycled as condenser coolant; the cost is approximately double that of once-through cooling. A still more expensive method substitutes vertical space for horizontal space by letting the heated water cool as it drips down through a lattice or tray structure in a cooling tower. If mechanical draft is used -- i.e., fans -- the structure can be smaller and cheaper but the operating costs higher than if natural draft is used. At Sacramento, the two natural draft towers dwarf the adjoining power plant. The principal cooling mechanism, even more than in the case of the cooling pond, is evaporation, and the possible effects on local weather in regard to rainfall, fog, or icing conditions must be considered. Any evaporative method of cooling loses a lot of water and presents two potential environmental problems: the concentration of dissolved solids, especially fertilizers, in the coolant, with an eventual need to dispose of this solution, and the need for replacement water that may be scarce in the area. If the water vapor added to the air creates problems or the loss of evaporated water is unacceptable, the heat alone may be delivered to the air by using closed cycle cooling towers, with the condenser water in a closed system from which heat is extracted by passing air over radiative fins. The costs of such systems are some 10 to 15 times those of the once-through system (40).

Among the environmental advantages of nuclear over fossil fuel power, the damaging effects of mining uranium may prove to be only a little less than for coal, even though 1 pound of uranium-235 is the theoretical equivalent in heat output of 3 million pounds of coal. So little of natural uranium is U-235 and uranium generally occurs in such low concentration in its ores that there is a much smaller advantage in total quantity of material mined than might have been anticipated. Choice of mining methods may make a greater difference, and both coal and uranium have been extracted by the environmentally destructive strip-mining technique in some places. Eventual use of breeder reactors should introduce a factor of 100 in favor of nuclear power in quantity of material to be mined.

It will be noted that this discussion singles out coal rather than oil or gas for comparison. Gas is least polluting and oil is next in order, while both are extracted with less damage to the environment, in general, than coal. As of 1963, however, recoverable coal was estimated to constitute 78% of the total U.S. fossil fuel energy resources (41). The critical present and predicted shortages of gas and the rapid depletion of our oil reserves continue to make coal even more important in relative terms.

One of nuclear power's potential advantages that should be exploited is the possibility of development of the area surrounding a plant as a recreational park. The owner of the plant is required to establish an "exclusion area" over which he has control so that, in case of emergency, he may deny access of the public. These areas are, in at least some cases, landscaped to enhance the appearance of the plant. Since nuclear plants are inoffensive in appearance and behavior -- no noise or smoke or odors, and the possibility of pleasing architecture -- it should be possible to allow public use of the area, since emergency evacuation of transient park visitors presents little difficulty. Visitors' centers are common to many present reactors and other entertaining or instructive features might be added; for example, a tiny bit of the condenser cooling water could maintain a heated swimming pool the year around.

As a final note, it is an interesting fact that, whereas the applicant for a nuclear power plant license is being subjected to an extensive and intensive process of formal scrutiny in accordance with the National Environmental Policy Act of 1969 (NEPA) (42), he could elect to build a fossil fuel plant of equal size at the same site and avoid that costly and time-consuming undertaking. The explanation, of course, is that NEPA prescribes that "all agencies of the Federal Government shall...include in...major Federal actions significantly affecting the quality of the human environment, a detailed statement by the responsible official on -- (i) the environmental impact of the proposed action," etc., etc. Licensing of a nuclear power plant, both at the construction stage and at the operating stage, is deemed to be a major Federal action and hence requires such a statement by the AEC. Judicial decisions interpreting NEPA in this context constitute a long story in themselves. Since no Federal action appears to be involved in getting permission to build a fossil fuel plant, NEPA has not been applied in such cases, though some lawyers speculate on the possibility that, where approvals by the Corps of Engineers or the Federal Power Commission become necessary, the action may be considered "major." For the present, the nuclear power plant not only appears to be a "good neighbor" evironmentally because of its inherent qualities and the prevailing engineering and architectural practices but also because a policeman is breathing down its neck.

REFERENCES

1. Hearings before the Joint Committee on Atomic Energy, Cong. of the U.S., 91st Cong., 1st Sess., on Environmental Effects of Producing Electric Power, Part 1, Oct. and Nov., 1969, U.S. Govt. Printing Office, Washington, D.C., 1969,* pp. 192-3.
2. Ref. (1), Power, pp. 824-1043. A revised version is available as U.S. Public Health Service publication BRH/DER 70-1, Mar., 1970, Radiological Surveillance Studies at a Boiling Water Nuclear Power Reactor.
3. Atomic Energy Act of 1946, Public Law 585, 79th Cong., 60 Stat. 755-75, 42 U.S.C. 1801-19.
4. Executive Order 10831, 24 F.R. 6669 (1959).
5. Public Law 373, 86th Cong., 73 Stat. 688, 42 U.S.C. 2021.
6. Reorganization Plan No. 3 of 1970, 35 F.R. 15623 (1970), Sec. 2 (a)(7).
7. Staff Reports of the Federal Radiation Council: Background Material for the Development of Radiation Protection Standards, Reports No. 1 (May 13, 1960), 2 (Sept. 1961), and 5 (July 1964).
8. Federal Radiation Council, Memorandum for the President, 25 F.R. 4402-3 (1960).

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* Cited elsewhere in list as "Ref. (1), Power"

9. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, General Assembly, Official Records: 17th Session, Supp. No. 16 (A/5216), United Nations, N.Y., 1962, p. 21.

10. U.S. Public Health Service, Report of the Medical X-ray Advisory Committee on Public Health Considerations in Medical Diagnostic Radiology (X Rays), Oct. 1967, U.S. Govt. Printing Office, Washington, D.C.

11. U.S. Public Health Service, Food and Drug Administration, Bureau of Radiological Health, BRH Bulletin, Vol. VI, No. 7, April 3, 1972.

12. Ref. (1), Power, p. 190.

13. J.B. Knox, Airborne radiation from the nuclear power industry, Nuclear News, Feb. 1971, pp. 27-32.

14. Ref. (1), Power, p. 622 ff.

15. Jack L. King, Genetics 58:625, April, 1968.

16. A.M. Stewart and G.W. Kneale, Lancet 1970, ii, 4.

17. ICRP Publication 14, Radiosensitivity and Spatial Distribution of Dose, Pergamon Press, Oxford, 1969, pp. 23, 105-6.

18. National Center for Health Statistics, Vital Statistics of the United States, 1968, Vol. II - Mortality, Part B, Rockville, Md., 1971.

19. U.S. Public Health Service, Raiological Health Handbook, Rev. Ed., Sept., 1960, Washington, D.C., 1960, p. 98.

20. Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Cong. of the U.S., 86th Cong., 1st Sess., on Industrial Radioactive Waste Disposal [**], Vol.2, Jan. and Feb., 1959, U.S. Govt. Printing Office, Washington, D.C., 1959, pp. 1722-87.

[**] Cited elsewhere in list as "Ref. (20), Waste Disposal"

21. *ibid*., p. 1762.

22. U.S. Atomic Energy Commission, Major Activities in the Atomic Energy Programs,*** Jan.-Dec., 1971, U.S. Govt. Printing Office, Washington, D.C., p. 31.

23. Joint Committee on Atomic Energy, Cong. of the U.S., 89th Cong., 1st Sess., Joint Committee Print, Selected Materials on Atomic Energy Indemnity Legislation, June, 1965,**** p. 31.

24. Ref. (1), Power, p. 240.

25. U.S. Public Health Service, Bureau of Radiological Health, An Investigation of Airborne Radioactive Effluent from an Operating Nuclear Fuel Reprocessing Plant, BRH/NERHL 70-3, Rockville, Md., 1970.

26. Ref. (22), AEC Report, Jan.-Dec., 1971, p. 76.

27. *ibid*., p. 77.

28. Ref. (20), Waste Disposal, Vol. 3, pp. 1938-2027.

29. *ibid*., pp. 2087-2279.

30. *ibid*., pp. 2095, 2225.

31. *ibid*., map, p. 2099.

32. Personal communication dated Mar. 22, 1972, J.D. Andrew, Jr., Chairman, Uniform Boiler and Presssure Vessel Laws Society, Inc., 57 Pratt St., Hartford, Conn.

33. For an extensive discussion of the ECCS problem and the present controversy, see Nuclear News, Jan. 1972, Vol. 15. The quotation is from Norman C. Rasmussen's favorable opinion; Daniel F. Ford reports an unfavorable opinion.

34. Ref. (22), AEC Report, Jan.-Dec., 1964, p. 136.

*** Cited elsewhere in list as "Ref. (22), AEC Report"

**** Cited elsewhere in list as "Ref. (23), Selected Materials"

35. Ref. (23), Selected Materials, pp. 169-179: A.J. Rosenthal *et al.*, Summary of report on catastrophic accidents in government programs.

36. Personal communication in 1963 from J.M. Smith, General Electric Co., who was a principal participant in operations following the accident.

37. M. Glasser *et al.*, Arch. Environmental Health 15:684, 1967, cited in V. Brodine, Environment 13:2, 1971

38. U.S. Environmental Protection Agency, Office of Research and Monitoring, Radiological Survey around Power Plants Using Fossil Fuel, EERL 71-3, Rockville, Md., 1970.

39. Donald E. Watson, The risk of carcinogenesis from long-term low-dose exposure to pollution emitted by fossil-fueled power plants, UCRL-50937, Lawrence Radiation Laboratory, Livermore, CA, 1970.

40. Ref. (23), Selected Materials, p. 30.

41. Hearings before the Joint Committee on Atomic Energy, Cong. of the U.S., 88th Cong., 1st Sess., on Development, Growth, and State of the Atomic Energy Industry, 1963, Part 1, U.S. Govt. Printing Office, Washington, D.C., 1963, p. 176.

42. Public Law 190, 91st Cong., 83 Stat. 852, 26 U.S.C. 5801 *et seq*.